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PETROLOGY FOR STUDENTS

AN INTRODUCTION TO THE STUDY OF ROCKS UNDER THE MICROSCOPE

by

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PREFACE TO FOURTH EDITION

THE following work, now offered in a further revised edition, has been written to serve as a guide to the study of rocks in thin slices, and is of course assumed to be supplemented throughout by demonstrations on actual specimens. Since it is designed primarily for the use of English-speaking students, examples are chosen, so far as is possible, from British, Colonial, and American rocks; and a like remark applies to the numerous references to original authorities which are inserted in foot-notes.

No systematic account is given of the crystallographic and optical properties of minerals. This is rendered unnecessary by such books as Iddings' *Rock-Minerals* and other well-known works. In particular, I have made no explicit reference to the use of convergent light.

In view of the difficulty of representing rock-sections adequately by means of process-blocks, I have often cited the coloured plates in some standard works of reference,

to which most students will have access. The figures given on the following pages are selected chiefly to illustrate simple structural characters, and some of them are necessarily rather diagrammatic. A number of new figures have been added for the present edition, and a few of the old ones have been withdrawn.

A. H.

ST JOHN'S COLLEGE, CAMBRIDGE.
January, 1908.

CONTENTS

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ABBREVIATIONS.

G.M. = Geological Magazine.

M.M. = Mineralogical Magazine.

Q.J.G.S. = Quarterly Journal of Geological Society.

A.J.S. = American Journal of Science.

CHAPTER I.

INTRODUCTION.

In this chapter will be included some notes on the optical properties of minerals, which may be of use to a novice; but there will be no attempt to supersede the use of books dealing systematically with the subject.

Microscope. We shall assume the use of a microscope specially adapted for petrological work, and therefore fitted with polarizing and analysing prisms, rotating stage with graduated circle and index, and 'cross-wires' of spider's web properly adjusted in the focus of the eye-piece. The sub-stage mirrors attached to such instruments usually have a flat and a concave face. With day-light the flat face should be used; with artificial light things should be so arranged that the mirror, used with the concave face, gives as nearly parallel rays as possible.

A double nose-piece, to carry two objectives, is very useful, although it usually gives very imperfect centring for high powers. The most useful objectives are a 1 inch or $1\frac{1}{2}$ inch and a $\frac{1}{4}$ inch, but for many purposes a $\frac{1}{8}$ inch is also very desirable. For minute objects, such as the 'crystallites' in glassy rocks and the fluid-pores in crystals, a high power is indispensable, and for very fine-textured sedimentary rocks an immersion-lens offers great advantages.

A selenite-plate, a quartz-wedge, and other special pieces of apparatus will be of use for various purposes. The methods

involving their use may be found in the mineralogical text-books; where too the student will find guidance as to the examination of crystal-slices by convergent light.

Form of section of a crystal and cleavage-traces. A well-formed crystal gives in a thin slice a *polygonal section*, the nature of which depends not only upon the forms present on the crystal, but also on the direction of the section and on its position in the crystal, as, *e.g.* whether it cuts through the centre or only truncates an edge or corner. Again, the same shape of section may be obtained from very different crystals. Nevertheless, if several crystals of one mineral are present in a rock-slice, we can by comparison of the several polygonal sections obtain a good idea of the kind of crystal which they represent. Further, if by optical or other means we can determine approximately the crystallographic direction in which a particular crystal is cut, we can usually ascertain what faces are represented by the several sides of the polygon.

For this purpose we may require to measure the angle at which two sides meet, and this is easily done with a microscope provided with a rotating stage and graduated circle. Bring the angle to the intersection of the cross-wires, adjust one of the two sides to coincide with one of the cross-wires, and read the figure at the index of the circle. Then rotate until the other side is brought to coincide with the same cross-wire, and read the new figure. The angle turned through is the angle between the two sides of the section.

This angle is the same as that between the corresponding faces of the crystal only provided the plane of section cuts these two faces perpendicularly. For a section nearly perpendicular to the two faces, however, the error will not be great.

In consequence of the mechanical forces which affect rock-masses, and also as a result of the process of grinding rock-slices, the minerals often become more or less fractured or even shattered. In a strictly homogeneous substance the resulting cracks are irregular; but if there be directions of minimum cohesion in crystals (cleavage), the cracks will tend to follow such directions, and will appear in a thin slice as fine parallel lines representing the *traces of the cleavage-planes*

on the plane of section. The regularity and continuity of the cracks give an indication of the degree of perfection of the cleavage-structure; but it must also be borne in mind that a cleavage making only a small angle with the plane of section will, as a rule, not be shown in a slice.

In the case of a mineral like augite or hornblende, with two directions of perfect cleavage, the angle which the two sets of planes make with one another is, of course, a specific character of the mineral, or at least characteristic of a group of minerals, such as the pyroxenes or the amphiboles. In a slice perpendicular to both the cleavages the traces will show the true angle. For any other direction of section the angle between the cleavage-traces will be different; but it will not vary greatly for slices nearly perpendicular to both the cleavages, and will often suffice for discrimination, as for instance between the 87° of the pyroxenes and the 55½° of the amphiboles. In a slice parallel to the intersection of the two cleavages the two sets of cleavage-traces reduce to one, and a slice of a mineral such as augite or hornblende which exhibits but one set of cleavage-traces may be assumed to be nearly parallel to the intersection of the cleavages.

A mineral not possessing any good cleavage often shows irregular cracks in rock-slices (*e.g.* quartz and usually olivine). This is especially the case in brittle minerals.

Transparency, colours, and refractive indices of minerals. Only a few rock-forming minerals remain opaque even in the thinnest slices: such as graphite, magnetite, pyrites, and pyrrhotite; usually hæmatite, ilmenite, limonite, and kaolin; sometimes chromite or picotite. These should always be examined in reflected light: the lustre and colour, combined with the forms of the sections and sometimes the evidence of cleavage, will usually suffice to identify any of these minerals. The great majority of rock-forming minerals become transparent in thin slices. Those which seen in hand-specimens of rocks appear opaque, are often strongly coloured in slices, while those which in hand-specimens show colours are frequently colourless in thin slices. In the case of many minerals these 'absorption-tints' are thoroughly characteristic;

but still more so are the differences of colour (pleochroism) in one and the same crystal according to the direction of the slice and the direction of vibration of a polarized beam traversing it, as noticed below.

The colours ascribed to minerals in the following pages and the epithet 'colourless' apply to thin slices of the minerals.

Apart from colour, the aspect of a mineral as seen in thin slices by natural light varies greatly according to its *refractive index*[1], and it is of great importance for the student to learn to appreciate at a glance the effects due to a high or a low refractive index.

If a thin slice of a single crystal be mounted by itself in some medium of the same colour and refractive index as the crystal, its boundaries and surface-characters will be invisible, while its internal structure may be studied to the best advantage. Quartz mounted in Canada balsam (both colourless and of very nearly the same refractive index) is almost invisible. If olivine, a colourless mineral of much higher refractive index, be mounted in balsam, its boundaries and the slight roughness of its polished surface will be very apparent[2]. In ordinary rock-slices, mounted in balsam, a roughened or 'shagreened' appearance may be taken as the mark of a mineral having a refractive index considerably higher than that of the medium used.

Again, a highly refringent mineral surrounded in the slice by others less highly refringent is seen to be more strongly illuminated than these, and this brightness is made more conspicuous by a dark boundary which is deeper in proportion to the difference in refractive index between the mineral in question and its surroundings. For these reasons a highly refringent crystal seems to stand out in relief against the rest of the slice.

[1] By this must be understood its *mean* refractive index. A crystal of any system other than the regular has in any section two refractive indices, the magnitudes of which depend further upon the direction of the section; but these differences in any one mineral are usually small as compared with the differences between the mean indices in different minerals.

[2] Cohen (3), pl. XLVIII, compare figs. 1 and 2.

Such considerations must be borne in mind in examining the minute inclusions in which many crystals abound. These inclusions may be of gas, of liquid (usually with a gaseous bubble), of glass, or a crystal of some other mineral; and these may be distinguished by observing that the depth of the dark border depends upon the difference in refractive index between the enclosing and the enclosed substance[1]. The most strongly marked border is seen when a gaseous is enclosed by a solid substance. A liquid-inclusion in a crystal has a less marked boundary, but a bubble of vapour in the liquid is strongly accentuated. A glass-inclusion is still less strongly marked off from its enclosing crystal, while a gas-bubble contained in it shews a very deep black border.

When two minerals (or a mineral and Canada balsam) are in contact with one another in a thin slice in such a position that their surface of junction is cut approximately at right angles by the plane of section, it is easy to determine which of the two has the higher refractive index[2]. For this purpose the illumination should be limited by a diaphragm placed below the stage, and a high-power objective focussed upon the line of junction at the upper surface of the slice. This line is then seen to be bordered by a narrow bright band on the side of the more highly refringent mineral and a narrow dark band on the other side. If the objective be depressed until the lower surface of the slice is in focus, these appearances are reversed.

The refractive indices of the several rock-forming minerals may be found in the tables or books of reference, but the student will find it useful to carry in his mind such a list as that given below.

Refractive indices of the common rock-forming minerals.

Very low (1·43–1·51): tridymite, sodalite, analcime and most other zeolites, (volcanic glasses), leucite.

[1] For figures of various inclusions in crystals see Cohen (3), pl. VIII–XIII; Rosenbusch-Iddings, pl. VI, VII; Sorby, *Q. J. G. S.* (1858), xiv, pl. XVI–XIX; Ward, *ibid.* (1875), xxxi, pl. xxx.

[2] For Becke's method of comparing the refractive indices of minerals in a rock-slice see Luquer, *Sch. of Mines Quart.* (1902), xxiii, 127–133; Iddings, *Rock Minerals* (1906), 114–117.

Low (1·52–1·63): felspars, nepheline, quartz, (Canada balsam), micas, calcite, dolomite, wollastonite, actinolite, melilite.

Moderate (1·63–1·645): apatite, tourmaline, andalusite, hornblende.

High (1·68–1·8): olivine, sillimanite, pyroxenes, zoisite, idocrase, epidote, garnets.

Very high (1·9–1·95): sphene, zircon.

Extremely high (2·0–2·7): chromite, rutile.

Extinction between crossed nicols. When the polarizing and analysing Nicol's prisms are used together, with their planes of vibration at right angles to one another ('crossed nicols')[1], if no object be interposed, there is total darkness ('extinction'); and the same is the case when a slice of any vitreous substance, such as obsidian, is placed on the stage. If, however, a slice of a crystal of any system other than the regular is interposed, there is in general more or less illumination transmitted, and often bright colours. On rotating the stage[2] carrying the object, it is found that extinction takes place for four positions during a complete rotation, these being at intervals of a right angle. In other words, there are two *axes of extinction* at right angles to one another and the slice remains dark only while these axes are parallel to the planes of vibration of the nicols, which are indicated by the cross-wires in the eye-piece. If we rotate the slice into a position of extinction and then remove the nicols, the cross-wires will mark the axes of extinction in the crystal-slice.

Without attempting to deal fully with this branch of physical optics[3], we may remark that all the optical properties

[1] In using the two Nicol's prisms, it should always be ascertained that they are crossed. For this purpose the rotating prisms are usually provided with catches in the proper positions, but the true test is total darkness when no object is interposed.

[2] In some microscopes, such as that devised by Mr A. Dick, the stage is fixed, and the two nicols rotate, retaining their relative position, an arrangement with several advantages. We shall assume for distinctness that the stage is made to rotate, as in the most usual models.

[3] The student is referred for this to such books as Rosenbusch (transl. Iddings), *Microscopical Physiography of the Rock-making Minerals* (1888), London; Luquer, *Minerals in Rock Sections*; Iddings, *Rock Minerals*, chap. III.

of a crystal are related to three straight lines conceived as drawn within the crystal at right angles to one another (the *axes of optic elasticity*) and to a certain ellipsoid having these three straight lines for axes (the *ellipsoid of optic elasticity*). The positions of the three axes may vary in different minerals, but they must always conform to the symmetry proper to the system, and the same is true of the relative lengths of the axes of the ellipsoid. The plane of section of any slice cuts the ellipsoid in an ellipse, the form and position of which depend upon the direction of the section (*ellipse of optic elasticity*), and the axes of extinction are the axes of this ellipse.

In certain cases the ellipse of optic elasticity may be a circle. For this any diameter is an axis, and accordingly we find that such a slice gives extinction throughout the complete rotation. In crystals of the triclinic, monoclinic, and rhombic systems there are two directions of section which give this result. They are perpendicular respectively to two straight lines in the crystal (the *optic axes*), which lie in the plane of two of the axes of optic elasticity, and are symmetrically disposed towards them. In crystals of the tetragonal and rhombohedral systems the two optic axes coincide with one another and with the unique crystallographic axis, and only slices perpendicular to this give total darkness. In the regular system, the ellipsoid being a sphere, the ellipse is always a circle, and all slices give total darkness between crossed nicols.

Crystals of the regular system are spoken of as singly refracting or optically isotropic, and their optical properties[1] are similar to those of a glassy or colloid substance. Crystals of the other systems are doubly refracting or birefringent, and they are divided into uniaxial and biaxial according as they have one or two optic axes.

It is evident that the chance of a slice cut at random from a birefringent crystal being perpendicular to an optic axis is very small. If more than one crystal of a given mineral be present in a rock-slice, and all remain perfectly dark between crossed nicols throughout a rotation, it is a safe conclusion that the mineral is a singly refracting one.

[1] That is, such of them as we are here concerned with.

Straight and oblique extinction. By bearing in mind that the ellipsoid of optic elasticity, and consequently all the optical properties of a crystal, must conform to the laws of symmetry proper to the crystal-system of the mineral, we can foresee all the important points as regards the position of the axes of extinction in crystals of the different systems cut in various directions. For instance, a longitudinal section of a prism of apatite (a hexagonal mineral) will extinguish when its length is parallel to either of the cross-wires: this is *straight extinction*. A longitudinal section of a prism of albite (a triclinic mineral) will, on the other hand, have axes of extinction inclined at some angle to its length: this is *oblique extinction*. It is to be noticed that these terms have no meaning unless it is stated or clearly understood from what direction in the crystal the obliquity is reckoned. In these examples we reckoned with reference to one of the crystallographic axes defined by the traces of known crystal-faces. Another character often utilised is the cleavage. Thus in a monoclinic mineral with prismatic cleavages, such as hornblende, we select a crystal so cut that the two cleavages give only one set of parallel traces. These traces are then parallel to one of the crystallographic axes (the vertical axis), and we examine the position of extinction with reference to this. First we bring the cleavage-traces parallel to one of the cross-wires, removing if necessary for this purpose one or both of the nicols, and note the figure indicated on the graduated circle. Then, with crossed nicols, we rotate until the crystal becomes dark, and again note the figure. The angle through which we have turned is the *extinction-angle*. Observe that if a rotation through, say, 15° in one direction gives extinction, a rotation through 75° in the opposite direction would have given the same. For most purposes we do not need to distinguish between the two directions of rotation, but take merely the smaller of the two angles.

To obtain a measurement of use in identifying a mineral we require more than the above. Slices of a crystal of hornblende cut in various directions along the vertical axis will give different extinction-angles, from zero (straight extinction) in a section parallel to the orthopinacoid to a

maximum value in a certain other section. This *maximum extinction-angle* is a specific character, being nearly the angle between the vertical crystallographic axis and the nearest axis of optic elasticity. We may determine it with sufficient accuracy for most purposes by noting the extinction-angles in two or three vertical sections of the same mineral in a rock-slice and taking the largest value obtained[1].

By attention to the following points it is in most cases possible to refer to its crystal-system an unknown mineral of which several sections are presented in a rock-slice:

Regular system: singly refracting; all slices extinguish completely between crossed nicols, as in glassy substances.

Tetragonal and Rhombohedral (including Hexagonal): birefringent and uniaxial; straight extinction for longitudinal sections of crystals with prismatic habit and for any sections of crystals with tabular habit. The two systems cannot be distinguished from one another by optical tests, but in cross-sections of prisms the crystal outline or cleavages will usually suffice to discriminate.

Rhombic (this and the remaining systems birefringent and biaxial): straight extinction for longitudinal sections of crystals with prismatic habit; sections perpendicular to the vertical axis have axes of extinction parallel to pinacoidal faces or cleavages and bisecting the angles between the traces of prism-faces or prismatic cleavages. A section *nearly* parallel to the vertical axis will give nearly straight extinction, except in minerals (*e.g.* hypersthene) which have a wide angle between the optic axes.

Monoclinic: two important types may be noticed according as the intersection of the chief cleavages (and direction of elongation of the crystals) lies in or perpendicular to the plane of symmetry. In the former case longitudinal sections may give any extinction-angle from zero up to a maximum value characteristic of the species or variety: in the latter (*e.g.* epidote and wollastonite) longitudinal

[1] On the relation between this maximum extinction-angle and the extinction-angle measured in a cleavage-flake of hornblende or augite, see *M. M.* (1893) x, 239, 240; and Daly, *Proc. Amer. Acad. Arts and Sci.* (1899) xxxiv, 311–323.

sections give straight extinction. The former case is the more frequent.

Triclinic: no sections give systematically straight extinction.

Twinning. The existence of twinning in a slice of a crystal is, in general, instantly revealed by an examination of the slice between crossed nicols, since the two individuals of the twin show different interference-tints, and extinguish in different positions[1]. When twin-plane and face of association coincide—the most common case—a slice perpendicular to the twin-plane will give in the two individuals of the twin extinction-angles which, reckoned from the line of junction, are equal but in opposite directions. Conversely, a crystal which gives equal but opposite extinction-angles may be assumed to be cut very nearly perpendicularly to the twin-plane. If the plane of section cut the twin-plane of a crystal at a very small angle, the two individuals of the twin will overlap for a sensible width, and we shall see between the two a narrow band which does not behave optically with either.

When repeated twinning occurs, as in felspars with albite lamellation, the lamellæ divide, as regards optical behaviour, into two sets arranged alternately.

Extinction-angles in felspars. The discrimination of the several felspars by means of their extinction-angles measured on cleavage-flakes, as perfected by Schuster, is a method of great precision, but is not applicable to crystals in rock-slices. For these the method advocated by Michel Lévy and others will often be found useful. There are two cases in which it is readily applied.

(i) *For crystals with albite-lamellation*:—Select sections cut approximately perpendicular to the lamellæ. These are known by the extinction-angles in the two alternating sets of lamellæ, reckoned from the twin-line, being in opposite directions and nearly equal; also by the illumination of the two sets of lamellæ being not very different when the twin-line

[1] The only exceptions (apart from opaque crystals) are in minerals, like the spinels, optically isotropic, and in cases in which the law of twinning is such that the directions of the axes of optical elasticity are not altered (*e.g.* quartz).

is parallel to a cross-wire. Measure the angles in question in three or four crystals so selected, and take the greatest value found. This will be very nearly the maximum angle for all such sections, which is a specific constant for each kind of felspar, as indicated for certain types in the annexed diagram (fig. 1). The values for types not given in the diagram may be judged with sufficient accuracy by interpolation, since the maximum extinction-angle changes steadily from one end of the series to the other. It will be noticed, however, that in certain cases different kinds of felspar (viz. those placed on the same vertical lines in the diagram) give equal angles, and in this connection two remarks are to be made.

(*a*) A slice of a crystal has two directions of extinction, at right angles to one another. Hitherto we have taken the angle to the nearest direction of extinction, but the diagram shews that for angles of 37° or more this introduces an ambiguity. It is then necessary to distinguish between the two directions (by means of the quartz-wedge or some other contrivance) and to select that one which corresponds with the least axis of the ellipse of elasticity (indicated by an arrow-head in the diagram). In this way anorthite and bytownite are discriminated from the medium labradorites. Other criteria may sometimes be used, *e.g.* the stronger birefringence of anorthite, as pointed out below[1].

(*b*) The signs + and – denote angles measured in opposite directions crystallographically. Unless other means of discrimination can be made use of, we have usually no way of distinguishing the two directions, and there is consequently an ambiguity between albite and the more basic oligoclases (with oligoclase-andesine). Since the latter have about the same refractive index as quartz and Canada balsam, while the index for albite is distinctly lower, a discrimination may sometimes be made by rough observations of comparative refringence.

[1] Another point worthy of notice is the frequency with which certain angles (less than the maximum) occur in a number of sections perpendicular to the albite-lamellæ. For anorthite the favorite angles are 32° and 41°, for medium labradorite 21° and 36°.

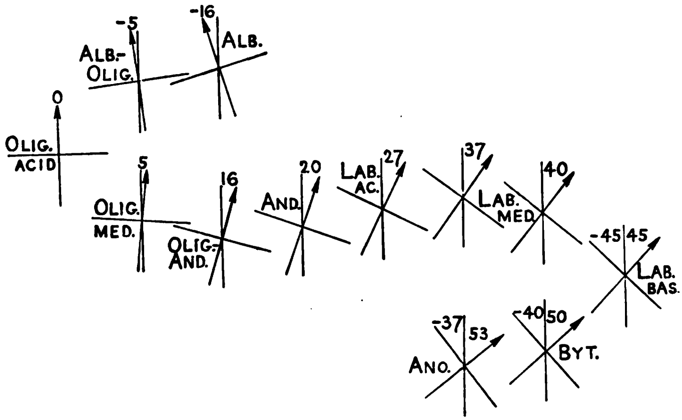

FIG. 1. MAXIMUM EXTINCTION-ANGLES OF PLAGIOCLASE FELSPARS IN SECTIONS AT RIGHT ANGLES TO THE ALBITE-LAMELLÆ.

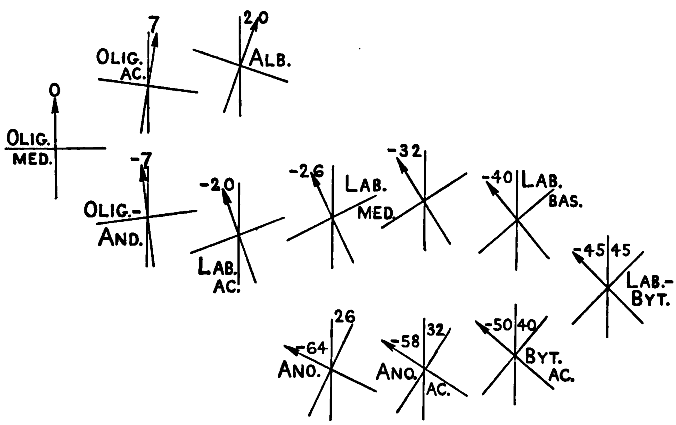

FIG. 2. MAXIMUM EXTINCTION-ANGLES OF PLAGIOCLASE FELSPARS IN LONGITUDINAL SECTIONS OF MICROLITES.

Summarily, we have the following characteristic angles for different felspars :—

0° to 5°, oligoclase, the more acid types.
6° to 16°, albite *and* the more basic oligoclases (with oligoclase-andesine).
16° to 22°, andesines.
27° to 45°, labradorites.
45° to 50°, bytownites.
50° and above, anorthites.

(ii) *For microlites*, assumed to have their length parallel to the intersection of the two principal cleavages :—Here we measure extinction-angles from the long axis of the microlites, and select the highest angle obtained by measurements on several microlites. The characteristic maxima for certain varieties of plagioclase are given in the annexed diagram (fig. 2), and the values for intermediate varieties can be interpolated. As before, there are two points to be noted.

(*a*) If the angle of extinction as measured is 26° or more, we must discriminate by the quartz-wedge or otherwise between the two directions of extinction.

(*b*) If the angle is 20° or less, an ambiguity occurs which cannot be removed by this method; viz. between albite and andesine or andesine-labradorite and between acid oligoclase and oligoclase-andesine. There is thus more unavoidable ambiguity in this case than in that of albite-lamellæ, as appears from the following values for different felspars.

0° to 7°, oligoclase with oligoclase-andesine.
8° to 10°, albite-oligoclase *and* andesine.
10° to 20°, albite *and* andesine-labradorite with acid labradorite.
30° to 42°, labradorite, medium to basic.
49° to 56°, bytownites.
58° to 64°, anorthites.

Becker[1] has suggested another test applicable to microlites, which may very conveniently be used to supplement the above;

[1] *18th Ann. Rep. U.S. Geol. Sur.* Part III (1898), 32–34, and *A. J. S.* (1898) v, 349–354, pl. III. For a more general account of the modern optical methods of discriminating the felspars see Winchell, *Amer. Geol.* (1898), xxi, 12–48, pl. II–VIII.

since, although it is of little use for the more basic varieties, it affords a useful criterion for distinguishing the oligoclases, andesines, *etc.* Instead of longitudinal sections, perpendicular cross-sections of the microlites are selected. These are small, nearly square, and sharply defined. The extinction-angles vary from $-13°$ for pure albite to $42\frac{1}{2}°$ for anorthite, and from Becker's figures we may deduce the following approximate values:—

$0°$ to $4°$, oligoclase, acid.
$4°$ to $7°$, oligoclase, medium, *and* albite-oligoclase.
$7°$ to $13°$, oligoclase, basic, *and* albite.
$18°$ to $22°$, andesine.
$26\frac{1}{2}°$ to $38°$, labradorite, acid to medium.
$38°$ to $42\frac{1}{2}°$, medium labradorite to anorthite.

If the sections selected for measurement be as much as $10°$ from the true perpendicular cross-section, the resulting error is only about $1\frac{1}{2}°$ to $2\frac{1}{2}°$ in the more acid half of the plagioclase series, and therefore does not vitiate the conclusion.

Zonary banding in felspars. In many rocks the felspars show between crossed nicols concentric zones roughly parallel to the boundary of the crystal, the successive zones extinguishing in different positions (fig. 3, *A*). (If there be albite-lamellation, we confine our attention to one of the two sets of lamellæ.) This difference in optical behaviour among the successive layers which build up the crystal may arise in two ways: firstly, from the successive zones being of different kinds of felspar-substance; or, secondly, from ultra-microscopic twinning affecting in various degrees the different layers of a crystal chemically homogeneous. This has been pointed out by Michel Lévy, and he gives a test which will resolve all except certain rare cases. It will be found, on rotating the slice between crossed nicols, that there are certain positions in which the albite-lamellæ disappear. If simultaneously with this the zonary banding disappears also, so that the whole crystal[1] is uniformly illuminated, the appearances can be explained by ultra-microscopic twinning alone: if this is not the case, the zonary banding may be ascribed to the successive

[1] Or if there be Carlsbad twinning also, the whole of one individual of the Carlsbad twin.

layers of felspar-substance in each crystal differing in chemical composition. When this occurs, the rule generally holds that the layers or zones become progressively more acid from the centre to the margin.

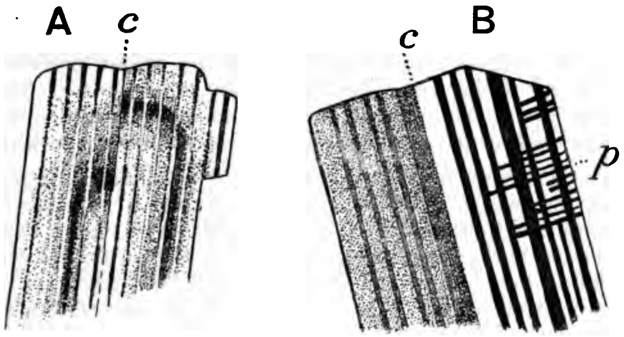

FIG. 3. PLAGIOCLASE CRYSTALS; × 14, CROSSED NICOLS.

A. Albite-lamellation combined with twinning on the carlsbad law (*c*) and with strong zonary banding.

B. Pericline-twinning (*p*) in addition to albite and carlsbad.

Interference-tints. We have remarked that a thin slice of a doubly refracting crystal, examined between crossed nicols, is in general not dark except when placed in certain definite positions. In any other position it does not completely extinguish the light, but its effect, in conjunction with the nicols, is partially to suppress the several components of the white light in different degrees, so that in the emergent beam these components are no longer in the proportions to give white light. In this way arise polarization-tints or interference-tints. These belong to a definite scale, known as *Newton's scale*, on which the several tints (though graduating into one another), are distinguished by names and divided into several 'orders.' The student should learn the succession of these tints, in the first place from the coloured plates accompanying some mineralogical works[1], but ultimately from the minerals themselves.

[1] Michel Lévy and Lacroix, *Les Minéraux des Roches*; Rosenbusch (transl. Iddings), *Microscopical Physiography of the Rock-making Minerals*; Iddings, *Rock Minerals*.

The precise position in the scale of a given tint observed between crossed nicols can be fixed by means of a quartz-wedge[1] or other contrivance for 'compensating' or neutralising the birefringence of the slice; but for ordinary purposes, at least with colourless or nearly colourless minerals, the interference-tint can be judged by eye with sufficient accuracy. The most brilliant colours are those of the second order and at the top of the first; the lowest colours of the first order are dull greys; while in the third and fourth orders the tints become brighter but paler, ultimately approximating to white.

The interference-tints given by a crystal-section depend (i) on the birefringence of the mineral, which is a specific character: (ii) on the direction of the section relatively to the ellipsoid of optic elasticity, the tint being highest for a section parallel to the greatest and least axes of the ellipsoid; (iii) on the thickness of the slice. These last two are disturbing factors, which must be eliminated before we can use the interference-tints as an index of the birefringence of the crystals, and so as a useful criterion in identifying the mineral.

The fact that the interference-tints depend in part on the direction of the section through the crystal will rarely be found to give rise to any difficulty in estimating roughly the birefringence of the mineral. If two or three crystals of the same mineral are contained in a rock-slice, it is sufficient to have regard to that one which gives the highest interference-tints. Even a single crystal will in the majority of cases give tints not so far below those proper to the mineral as to occasion error, but the possibility of the section having an unlucky direction must be borne in mind.

Rock-slices prepared by a skilful operator are in most cases so nearly constant in thickness that variations in this respect may be left out of consideration. Any important difference is

[1] The edge of the quartz-wedge is usually not thin enough to give the lowest tints of the scale. This can be remedied by means of a film of mica, properly oriented: see Mahony, *Nature*, 2 August, 1906, lxxiv, 317, 318. On some special applications of the quartz-wedge, see Evans, *M. M.* (1905) xiv, 87–92. On the mica-wedge, which for many purposes affords an efficient substitute, see Dick, *Notes on a New Form of Polarizing Microscope* (1890).

at once detected by well-known minerals giving unusual interference-tints. Thus, if quartz or orthoclase give the yellow of the first order, the slice is rather a thick one; if they give orange or red, the slice is considerably thicker than the average of good preparations. Knowing this, we can make allowance for it in estimating the birefringence of some doubtful mineral in the same slice. Such allowance can be roughly judged, or it can be made with considerable precision by means of the large coloured plate of Michel Lévy and Lacroix[1].

The actual birefringence (numerically expressed) of the several rock-forming minerals, and the interference-tints which they afford in slices of ordinary thickness, are given in numerous books and tables. For rough purposes the student will find it useful to remember about as much as is contained in the following table.

Birefringence and interference-tints of the commoner rock-forming minerals. (The colours given are for slices ·001 inch in thickness.)

Very weak (giving steel-grey tints): leucite, apatite, nepheline, melilite.

Weak (giving blue-grey to white of first order): zoisite, microcline, orthoclase, albite, oligoclase, andesine, labradorite, quartz, bytownite, enstatite.

Moderate (giving white, yellow, or orange of first order): andalusite, chlorite, anorthite, hypersthene.

Strong (giving red of first order to violet and blue of second): tourmaline, augite and diallage, common hornblende and actinolite.

Very strong (giving green, yellow, or orange of second order): olivine, epidote, talc, biotite, muscovite.

Extremely strong (giving the pale colours of the third and fourth orders to almost pure white): zircon, hornblende rich in iron, sphene, calcite and dolomite, rutile.

Note that in minerals with strong absorption, such as the deep-coloured micas and hornblendes, the interference-colours are more or less masked by those due to absorption.

[1] This plate can be purchased separately and mounted as a wall-diagram. On the method of using it see Pirsson and Robinson, *A. J. S.* (1900) x, 260–265; Joly, *Sci. Pr. Roy. Dubl. Soc.* (1901) ix (N.S.), 485–488.

Pleochroism. A character often useful in identifying minerals is pleochroism, the property of giving different absorption-tints for different directions of vibration of the light within the crystal. To observe this property, we use the lower nicol only, and rotate either it or the stage. The direction of vibration is that of the shorter diagonal of the nicol.

It is necessary not only to observe the changes of colour, if any, but also to note their relation to directions of vibration within the crystal. For example, elongated sections of biotite and hornblende, tourmaline and sphene, may be found to change from a deeper to a paler tint of brown on rotation; but while in the first pair of minerals the direction of vibration most nearly coincident with the long axis of the section gives the deeper tone, in the second pair it gives the paler.

To be more precise, we wish to know, for a specification of the pleochroism of a given mineral, the absorption-tints for vibrations in three definite directions within the crystal—those of the three axes of optical elasticity. Taking a given mineral, say a hornblende, of which a number of crystals occur in our slice, we may proceed as follows. Select a crystal showing only one set of cleavage-traces and giving the maximum extinction-angle: this section will be approximately parallel to the plane of symmetry, and will contain two of the required axes. These axes are the axes of extinction for the section, and their positions are thus easily found. The one nearest to the cleavage-traces is the γ-axis, the other the α-axis. Bring the γ-axis to coincide in direction with the shorter diagonal of the nicol, adjusting the position by obtaining extinction, and then removing the upper nicol. Observe the colour: then do the same for the α-axis. For the remaining β-axis we must use another crystal. We may choose one showing only a single set of cleavage-traces and giving straight extinction: the β-axis is perpendicular to the cleavage-traces. Or we may choose a section showing two sets of cleavage-traces intersecting at a good angle and extinguishing along the bisectors of the angles between the cleavage-traces: the β-axis is the bisector of the acute angle.

Minerals of the rhombohedral and tetragonal systems can have only two distinct absorption-tints (*dichroism*), one for

vibrations parallel to the longitudinal axis (extraordinary ray), the other for vibrations in any direction perpendicular to it (ordinary ray). In the regular system the absorption-colours are independent of direction.

In consequence of pleochroism the absorption-tints of a mineral vary in differently cut crystals seen in natural light, but the precise nature of the pleochroism can be investigated only with a polarized beam.

Examination of a rock-slice. In studying a rock-slice it is always well to proceed methodically. A low power should first be used: any object which it is desirable to examine under a higher magnification should be brought to the centre of the field before the objective is changed for a higher power. The slice should always be observed first in natural light: by their outline, relief, cleavages, inclusions, alteration-products, *etc.*, all the ordinary rock-forming minerals can be identified in most cases without the use of polarized light. If the lower nicol is not readily movable it may be left in for many purposes; but it must be remembered that half the illumination is thus cut off, and for any but the lowest magnifying powers this is of importance. Opaque substances should always be viewed in reflected light.

To examine the pleochroism of any coloured constituent, we put in the lower nicol, and rotate either it or the stage. For verifying feeble pleochroism the former plan is preferable, but the nicol must be rotated until its catch holds it before proceeding to the use of the two nicols, which will be the next act.

For some purposes oblique illumination is advantageous. For instance, the extremely slender needles of apatite in certain lamprophyres and other rocks become visible only by this means. A 'spot-lens' may be improvised by placing beneath the stage a convex lens of short focal length with its central part covered by a disc of black paper.

In using a high power it will be noticed that the focus is very perceptibly different for the upper and lower surfaces of the slice. To make out the form of a body enclosed in the

thickness of the slice the focus should be gradually moved, so as to bring different depths successively into view.

It cannot be too strongly insisted that the identification of the component minerals of a rock is only a part of the examination. The mutual relations of the minerals and their structural peculiarities must also be observed, the order of crystallization, intergrowths, interpositions, decomposition-products, pseudomorphs, *etc.*, as well as special rock-structures such as fluxion-phenomena, vesicles, effects of strain and fracture, *etc.* In short, the object of investigation should be not merely the composition of the rock, but its history.

Classification and nomenclature of rocks. Petrology has not yet arrived at any philosophical classification of rocks[1]. Further, it is easy to see that no classification can be framed which shall possess the definiteness and precision found in some other branches of science. The mathematically exact laws of chemistry and physics, which give individuality to mineral species, do not help us in dealing with complex mineral aggregates, and any such fundamental principle as that of descent, which underlies classification in the organic world, has yet to be found in petrology. Rocks of different types are often connected by insensible gradations, so that any artificial classification with sharp divisional lines cannot truly represent the facts of nature. At present, therefore, the best arrangement is that which brings together as far as possible, for convenience of description, rocks which have characters in common, the characters to be first kept in view being those which depend most directly upon important genetic conditions. The grouping adopted below must be regarded as one of convenience rather than of principle.

In a perfect system the nomenclature should correspond with the classification. This is, of course, impossible at present in petrology. Moreover great confusion has arisen in the nomenclature of rocks in consequence of the rapid growth of descriptive petrography. Many of the names still in use are older than the modern methods of investigation: they were given at a time when trivial distinctions were emphasized,

[1] For a historical sketch of the subject see Cross, *Journ. Geol.* (1902) x, 331–376, 451–499.

while rocks essentially different were often classed together. Later writers, each in his own way, have arbitrarily extended, restricted, or changed the application of these older names, besides introducing new ones. The newer rock-names need cause no confusion, provided they are employed in a strict sense. Thus 'foyaite' should be used for rocks like that of Foya, specimens of which are in every geological museum: to extend the name of all nepheline-bearing syenites is to introduce needless ambiguity. In practice perhaps the most convenient usage is to speak of 'the Foya type,' 'the Ditro type,' *etc.*, referring in each case to a described and well-known rock. There remain the names employed for families of rocks: some of these are old names, such as granite and syenite, which have come to have a tolerably well understood signification, not always that first attached to them; others, such as peridotite, have been introduced to cover rocks not recognized as distinct families by the earlier geologists. A division of a family is often designated by prefixing the name of some characteristic mineral of that division; *e.g.* hornblende-granite, hypersthene-andesite, *etc.*

These remarks apply more especially to igneous rocks, which we shall consider first. Such rocks, formed by the consolidation of molten 'magmas,' differ from one another in character, the differences depending partly on the composition of the magma in each case, partly on the conditions attending its consolidation. The composition is to some extent indicated by the essential minerals of the rock, which thus become an important, if not logically the prime, factor in any genetic classification. It is evident, however, that a mere enumeration of the minerals of a rock, without taking account of their relative abundance, cannot give a very precise idea of the bulk-analysis[1]; while, on the other hand, it appears on examination that magmas of very similar composition may, under different conditions of consolidation, give rise to widely different mineral-aggregates. Again, many rocks consist only in part of definite minerals, the residue being of unindividualised matter or 'glass.'

[1] This difficulty is only partially evaded by ranking some of the constituent minerals as *essential* and others as *accessory*.

To diverse conditions of consolidation must be referred differences in coarseness or fineness of texture, the presence or absence of any glassy residue, the evidence of one or more than one distinct stage in the solidification, and, in general, the peculiarities in the mutual arrangement of the constituent minerals, which collectively are termed the 'structure' of the rock.

The massive igneous rocks will first be divided into three groups: abyssal or *plutonic*, *hypabyssal*, and superficial or *volcanic*. These names express the different geological relations of the several groups as typically developed, but the divisions themselves are based upon the characteristic structural features which different conditions of consolidation have impressed upon the rocks. Under each of these three heads the various rock-types will be grouped in families founded proximately on the mineralogical, ultimately on the chemical, composition, though this cannot be done without some few inconsistencies. The families will be arranged roughly in order from the more acid to the more basic, but it must be remembered that such an arrangement in linear series can represent only very imperfectly the manifold diversity met with among igneous rocks.

A. PLUTONIC ROCKS.

THE rock-types to be treated under the head of plutonic or abyssal are met with, in general, in large rock-masses which have evidently consolidated at considerable depths within the earth's crust. Transgressive as regards their actual upper boundary, their geological relations on a large scale are, as a rule, only imperfectly revealed by erosion; so that their actual form and extent are often matters of conjecture. Some of the masses seem to be of the nature of great laccolites; others have been supposed to mark reservoirs of molten magma, which once furnished the material of minor intrusions and surface volcanic ejectamenta. The immediate apophyses of the large masses have similar petrographical characters.

The distinctive features of these rocks of deep-seated consolidation are those which point to slow cooling (not necessarily slow consolidation) and great pressure. The rocks are without exception *holocrystalline*, *i.e.* they consist wholly of crystallized minerals, with no glass. The texture of plutonic rocks may be comparatively coarse, *i.e.* the individual crystals of the essential minerals may attain considerable dimensions. The typical structure is that known as *hypidiomorphic*, only a minor proportion of the crystals being 'idiomorphic' (*i.e.* developing their external forms freely), while the majority, owing to mutual interference, are more or less 'allotriomorphic' (taking their shape from their surroundings)[1].

Sequence of crystallization. The terms just introduced are used with a relative signification; so that a given

[1] This is the terminology used by Rosenbusch. Zirkel has adopted Rohrbach's terms *automorphic* and *xenomorphic* in the same senses. Pirsson has suggested the term *anhedron* (with adjective *anhedral*) for a crystal not possessing external crystal-faces: *Bull. Geol. Soc. Amer.* (1895) vii, 492.

mineral in a rock may be allotriomorphic towards certain associated minerals and idiomorphic towards others. By observing such points we are able to make out the order in which the several minerals composing an igneous rock have crystallized out from the parent rock-magma. It is found that there is in many plutonic rocks a 'normal order of consolidation' for the several constituents, which holds good with a high degree of generality. It is in the main, as pointed out by Rosenbusch, a law of 'decreasing basicity.' The order is briefly as follows.

I. Minor accessories (apatite, zircon, sphene, garnet, *etc.*) and iron-ores.

II. Ferro-magnesian minerals :—olivine, rhombic pyroxenes, augite, ægirine, hornblende, biotite, muscovite.

III. Felspathic minerals :—plagioclase felspars (in order from anorthite to albite), orthoclase (and anorthoclase).

IV. Quartz, and finally microcline.

In many rocks such minerals as are present follow the above order. The most important exceptions are the intergrowth of orthoclase and quartz and the crystallization of quartz in advance of orthoclase in some acid rocks, and the variable relations between groups II. and III. in the more basic rocks. The order laid down applies in general to parallel intergrowths of allied minerals : thus when augite is intergrown with ægirine or hornblende, the former mineral forms the kernel of the complex crystal and the latter the outer shell ; when a plagioclase crystal consists of successive layers of different compositions, the layers become progressively more acid from the centre to the margin.

Certain constituents having variable relations are omitted from the foregoing list. Thus nepheline and sodalite belong to group III., but may crystallize out either before or after the felspars.

Varieties of structure in plutonic rocks. The typical structure of rocks of plutonic habit is that implied in the foregoing remarks, and is known as the *granitoid* or

'eugranitic' structure[1]. Among the more special modifications frequently met with are those depending upon the simultaneous crystallization of two of the essential minerals, giving rise to the so-called 'graphic' intergrowths, usually on a microscopic scale. The resulting *micrographic*, micropegmatitic or granophyric structure is most common in the quartz-bearing rocks, and arises there from an intimate interpenetration of part of the felspar with quartz (fig. 8, *B*). Within a certain area of a slice the quartz of such an intergrowth behaves optically as if it were a single crystal, the whole becoming dark between crossed nicols in one position. On rotation the felspar can be made to extinguish in its turn. Intergrowths of other minerals (*e.g.* augite and felspar) are less common. In both granitoid and micrographic rocks there sometimes occur vacant interstitial spaces or little cavities of irregular shape, into which project the sharp angles of well-formed crystals. Such rocks are said to have a *miarolitic* or drusy structure, but this peculiarity is often obscured by secondary products occupying the druses.

Opposed to the granitoid is the *granulitic* structure. In this a section of the rock appears as a mosaic of roughly equidimensional grains, usually of small size. There is in some cases a tendency to crystallographic development, or again the earlier-formed minerals tend to take on rounded outlines. The structure probably results from movement during the process of consolidation, and we shall see that very similar appearances may be produced by the deformation and crushing of already solidified granitoid rock-masses.

Both granitoid and granulitic rocks sometimes exhibit in greater or less degree a *parallel* disposition of elongated or tabular crystals of felspar, mica, *etc.*, indicative of some flowing movement of the rock-magma subsequent to the separation of those crystals. With this there may be a certain banding of the rock, due to alternations of slightly different types (mineralogically or structurally), which is known as a *gneissic* structure. These characters, however, may also have a quite different and secondary origin.

[1] The term 'granolite,' applied to such rocks by some American writers, is ill chosen, as likely to be confused with 'granulite.'

Traversing plutonic rock-masses of normal structural types, or bordering them as an irregular fringe, may often be found strikingly coarse-textured or *pegmatitic* modifications, with a strong tendency to graphic intergrowths[1]. While clearly related to the associated plutonic rock-masses, these pegmatitic rocks differ from them mineralogically in the sense of being somewhat more acid, and they are further characterized by the frequent occurrence of special minerals, often including compounds of the rarer chemical elements. They are usually regarded as representing the final (pneumatolytic) phase of consolidation of the rock-magmas from which they were formed. The lighter-coloured veins and streaks often seen traversing plutonic rocks are in many respects comparable with the pegmatites. They invariably show a coarser texture and a more acid composition than the main mass in which they occur; and, though they more or less clearly cut the latter, the relations are such as to prove that their origin is bound up with that of the main rock-mass. They are sometimes spoken of as (relatively) *acid excretions* from the crystallizing magma.

Contrasted with these, there occur in many plutonic rocks darker and finer-textured ovoid or irregularly rounded patches which are usually considered as (relatively) *basic secretions* from the magma, belonging to an early stage in the process of consolidation. Composed in general of the same minerals as the enclosing rock, they are richer in the earlier-formed—which are also the denser and more basic—constituents. The lighter-coloured veins, on the other hand, are relatively rich in the later-formed and more acid minerals.

The typical plutonic rocks are *non-porphyritic, i.e.* there is evidence of but one continuous process of consolidation. In many hypabyssal and almost all volcanic rocks, some one, or more, constituent (usually a felspar) occurs in two distinct generations with different habits and characters, belonging to an earlier and a later stage of the consolidation. This is the 'porphyritic' structure, and is typically wanting among plutonic

[1] The original pegmatite of Haüy was such an intergrowth of quartz and felspar ('graphic granite'), but the modern usage of the name is more extended.

rocks, which have what has been termed an 'even-grained' character ('körnig' of Rosenbusch). In some of the plutonic rocks, however, and especially among the granites, occur relatively large crystals of felspar, which give a *porphyritic* character to the rock of which they form part, and perhaps point to different conditions from those under which the main mass of the rock consolidated; but even here there is no sharp division between an earlier and a later period of crystallization, such as is indicated in the volcanic rocks.

We shall consider the several families in an order which corresponds roughly with their chemical relationship, beginning with the acid rocks and ending with the ultrabasic.

CHAPTER II.

GRANITES.

THE granites are even-grained holocrystalline rocks composed of one or more alkali-felspars, quartz, and some ferro-magnesian mineral, besides accessory constituents. The rocks are generally of medium to rather coarse grain, and the tendency of the crystals as a whole to interfere with one another's free development gives what Rosenbusch styles the hypidiomorphic structure.

According to their characteristic minerals, after felspars and quartz, the rocks are described as *muscovite-*, *biotite-*, *hornblende-*, and *augite-granites*; and this division corresponds often with different chemical compositions, from more to less acid types. *Tourmaline-granite* must be considered a special modification of the above, and, in particular, of the more acid kinds. With the granites we shall also include certain rocks (*aplite, pegmatite, greisen*) associated with granites but differing from them in important structural and mineralogical characters. Some of them never form, like the true granites, large bodies of rock.

Constituent minerals. Felspars make up the greater part of a granite, a potash- and a soda-bearing felspar commonly occurring together. The potash-felspar is often *orthoclase*, either in simple crystals or in Carlsbad twins, the Baveno twin being uncommon. When fresh, it shows its cleavages and sometimes a slight zonary banding, but these appearances are lost when the mineral is altered to any extent. The

common decomposition-processes give rise either to finely divided kaolin or to minute flakes of mica. When the latter are large enough to be clearly distinguished, they are often seen to lie along the cleavage-planes of the felspar. Decomposition often begins in the interior of a crystal, which may be clouded or completely obscured while the margin remains clear. Instead of orthoclase we may find *microcline*, which is usually the last product of consolidation in the rock. When fresh, microcline shows its characteristic 'cross-hatched' structure and sometimes a vein-like intergrowth of albite (fig. 4).

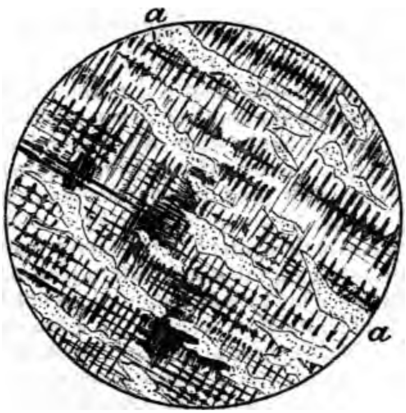

FIG. 4. MICROCLINE FROM THE 'RAPAKIWI' GRANITE OF FINLAND; × 20, WITH CROSSED NICOLS.

Showing the characteristic 'cross-hatching.' It is traversed by veinlets of albite (*a*) intergrown with crystallographic relation to the microcline [1031].

Some petrologists hold that the peculiar microcline-structure, due to fine twin-lamellation in two directions, is not essential, and may be set up in some cases as a secondary effect of strain; and that the quasi-monoclinic mineral orthoclase is merely microcline in which the twin-lamellation is carried to an ultra-microscopic degree of fineness[1]. The alteration of

[1] *Cf.* Teall, *Ann. Rep. Geol. Sur.* for 1895, p. 24; Keyes, 15*th Ann. Rep. U. S. Geol. Sur.* (1895), 711, 712.

microcline by weathering is similiar to that of orthoclase. The soda-felspar of most granites ranges from *albite* to *oligoclase*. It has rather a tabular habit, giving rise to elongated rectangular sections. It is always twinned on the albite- and occasionally too on the pericline-law. The common decomposition-products are kaolin, sometimes paragonite mica, and in the lime-bearing varieties some epidote or calcite. The most typical 'soda-granites' contain albite to the exclusion of potash-felspars, but this is an exceptional type. Parallel intergrowths of orthoclase and plagioclase are sometimes found (microperthite). The felspars of granite are not rich in inclusions, but they may enclose sparingly microlites of the earlier constituents of the rock.

The *quartz* of granites does not usually show the crystal boundaries, except on the walls of drusy cavities ('miarolitic' structure), or less perfectly when the mineral is enclosed by microcline. Its most characteristic inclusions are fluid-cavities: these are sometimes in the form of 'negative crystals,' either dihexahedral pyramids or elongated prisms; more usually the shape is rounded or irregular. These fluid-pores often occur with a definite arrangement along certain planes, appearing in a section as lines. The enclosed liquid does not fill the cavity, but leaves a bubble, which is mobile. In some cases the liquid is brine, and contains minute cubes of rock-salt (Dartmoor). In others liquid carbonic acid occurs instead of, or in addition to, water, and in some cases we see one bubble within another. Glass- and stone-cavities are less abundant. Sometimes extremely fine needles are enclosed (Peterhead): these seem to be rutile, and sometimes show the characteristic knee-shaped twin.

The dark micas of granites are usually termed *biotite*. This may be considered to include varieties rich in ferrous oxide (the haughtonite of many Scottish and Irish granites), or in ferric oxide (lepidomelane). The mineral builds roughly hexagonal plates, which, cut across, give an elongated section showing the strong basal cleavage. A lamellar twinning parallel to the base is probably common, but, owing to the nearly straight extinction, this is not often conspicuous. The fresh biotite is deep brown with intense pleochroism. Its

common inclusions are apatite, zircon, and magnetite, and the minute zircons are always surrounded by a 'halo' of extremely deep colour and intense pleochroism (fig. 6, *A*). Decomposition often produces a green coloration and ultimately a green chloritic pseudomorph with secondary magnetite-dust. This magnetite may be reabsorbed, restoring the brown colour but with less pleochroism and with loss of cleavage.

The colourless, brilliantly-polarizing *muscovite* forms rather ragged flakes, posterior to the biotite or partly in parallel intergrowth with it (fig. 6, *A*). It is always clear, and is not susceptible to weathering. A lithia-mica, in large flakes, takes the place of muscovite in some greisens and pegmatites.

The crystals of *hornblende* are irregularly bounded, or at least without terminal planes. They show the prismatic cleavage, and occasionally lamellar twinning parallel to the orthopinacoid. The colour is green or brownish-green, with marked pleochroism, and the extinction-angle in longitudinal sections always low. Besides inclusions of earlier minerals, there may be an intergrowth with biotite. The common decomposition-products are a green chloritic substance or an epidote and quartz.

When *augite* occurs, it is commonly the variety malacolite or diopside, colourless in slices. It is not usually in perfect crystals, but an idiomorphic green augite is found in some coarsely granophyric types of rock (Mull, fig. 8, *A*). Augite may be either uralitized or decomposed into a green chloritic mineral or into a mixture of serpentine and calcite. The augite is sometimes accompanied by a rhombic pyroxene (enstatite, Cheviot), and in one remarkable group of granitic rocks the dominant ferro-magnesian element is *hypersthene*.

Iron-ores are not plentiful in granites. *Magnetite* may occur or *hæmatite*, either opaque or deep-red; *pyrites* is also found as an original mineral.

Acute-angled crystals of light-brown pleochroic *sphene* (titanite) are often seen, and in the less acid granites are abundant (fig. 5, *B*). Rounded grains may occur instead. The high refractive index and other optical properties enable the mineral to be readily identified. The little prisms of *zircon* are even more highly refractive; but when they occur,

as they often do, enclosed in the biotite, the pleochroic halo is liable to obscure their nature. *Apatite* builds narrow colourless prisms, and often penetrates the biotite. Small reddish *garnets* occur in some muscovite-granites and aplites (Dublin): other unusual minerals are *cordierite*, usually pseudomorphed by the micaceous substance termed pinite, and *andalusite*, coated with flakes of muscovite. In some granites from America and elsewhere *allanite* (orthite) is found[1], while others contain epidote, often with an intergrown core of allanite[2]. Though epidote is a well known weathering-product in granitic rocks, this relation to allanite and the occasional inclusion of good crystals of epidote in flakes of biotite seem to point to its primary origin in these cases.

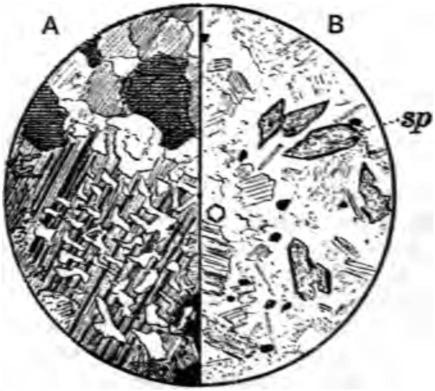

FIG. 5.

A. Micrographic intergrowth of plagioclase felspar and quartz in granite, St David's; × 20, *crossed nicols* [293]. *B*. Crystals of sphene (*sp*) in dark basic secretion in Shap granite, Westmorland; × 20 [1070].

Tourmaline characterizes a common modification of granite, especially near the margin of a mass. It may be in good crystals but more frequently has ragged outlines. The rude

[1] Iddings and Cross, *A. J. S.* (1885) xxx, 108–111; McMahon, *G. M.* 1899, 194–196 (Lairg).

[2] Hobbs, *A. J. S.* (1889) xxxviii, 223–228; *Amer. Geol.* (1893) xii, 218, 219.

cross-fracture is often apparent. The colour is brown, sometimes with patches of blue, and the dichroism is strong, the strongest absorption being for vibrations transverse to the long axis (the 'ordinary' ray).

Structure. In the granites the normal order of crystallization of the constituent minerals rules in most cases. The minor accessory minerals crystallized out first, and are thoroughly idiomorphic, *i.e* have taken their shape without external interference. The ferro-magnesian minerals have in general preceded the felspars, being often embraced or even enclosed by them, though the felspars may tend also to take on partial crystal-outlines. Rarely does, *e.g.*, mica occur interstitially to felspar. Biotite moulded on muscovite is not so rare. Apart from micrographic structures, the felspars, except microcline, have crystallized prior to the quartz, exceptions being infrequent. Where micrographic intergrowths occur, the felspar may be either orthoclase or a plagioclase (fig. 5, *A*). We need not further specify other structural peculiarities such as the miarolitic, the porphyritic, and the spheroidal or orbicular[1].

The banded or gneissic character, which sometimes affects granitic rocks over extensive regions, will be briefly noticed below.

Leading types. Almost all the true granites contain a brown mica. If a white mica be present in addition, we have *muscovite-granite* ('two-mica granite' or 'granite proper' of the Germans, 'granulite' of the French[2], 'binary granite' of some American writers[3]). Such rocks are commonly somewhat more acid in composition than those with dark mica only. The Carboniferous granites of Cornwall and Devon afford good examples. They consist of orthoclase, a

[1] Hatch, *Q. J. G. S.* (1888) xliv, 548–559, pl. XIV (Mullaghderg in Donegal), with a summary of information on spheroidal granites in general; Turner, *Journ. Geol.* (1899) vii, 154 (Bridal Veil in Yosemite Park); Harris, *G. M.* 1898, 11–13 ('Rapakiwi' granite of Finland); Adams, *Bull. Geol. Soc. Amer.* (1898) ix, 163–172 (Pine Lake, Ontario).

[2] The granulite of German and English petrologists has a different signification.

[3] This term, however, has also been applied to rocks consisting essentially of felspar and quartz, without mica.

plagioclase, quartz, and two micas[1], with the normal order of crystallization. The quartz has fluid-cavities, often enclosing minute cubes of rock-salt[2] (Dartmoor). Parallel intergrowths of biotite and muscovite are common. The minor constituents of the rock are magnetite, apatite, and zircon, the last, when it is enclosed in the biotite, being always encircled by the characteristic halo of intense pleochroism. More exceptional accessory minerals are andalusite, in pleochroic crystals coated by flakes of muscovite (Cheesewring), and 'pinite' pseudomorphs

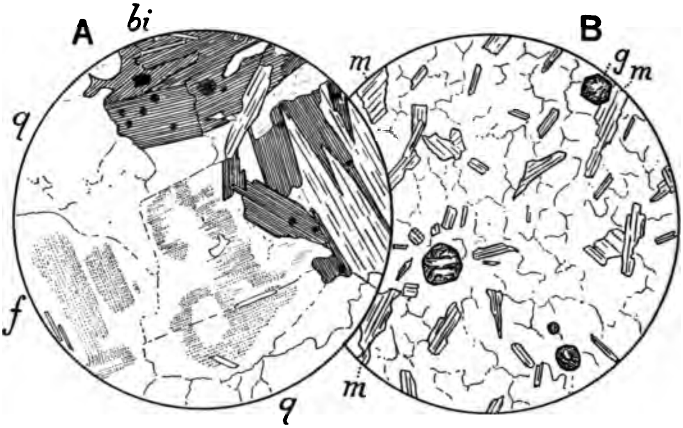

FIG. 6. GRANITIC ROCKS, KILLINEY, NEAR DUBLIN; × 20.

A. Muscovite-Biotite-Granite: composed of two micas (partly in parallel intergrowth), two felspars, and clear quartz (*q*). The biotite (*bi*) shows strongly pleochroic haloes, round minute enclosed zircons. The plagioclase felspar (*f*) is often turbid in the interior, owing to alteration [4436].

B. Aplite, veining the preceding rock: a finer-grained aggregate of quartz and felspars (plagioclase and microcline), with abundant flakes of muscovite (*m*) and scattered crystals of garnet (*g*) [4439].

[1] Dr Haughton's analyses of the Trewavas Head rock proved the felspar to be albite, the dark mica lepidomelane, and the white mica lepidolite; *Q. J. G. S.* (1869) xxv, 166, 167.

[2] Hunt, *G. M.* 1894, 102–104, with figures; Adye's *Stud. Micropetr.* p. 22, with figures.

after cordierite (Land's End). Tourmaline is common, and the rocks graduate into tourmaline-granites, especially near the margin of an intrusion.

The post-Ordovician granites which occupy so large a tract in Leinster[1] (*e.g.* near Dublin) are of a different type (fig. 6, *A*). They also have two micas, often in parallel intergrowth, and apatite and zircon are characteristic accessories; but the potash-felspar is microcline[2], and is the latest product of crystallization A plagioclase felspar is plentiful, and exceptionally albite is the only felspathic element present (Croghan Kinshelagh in Wexford). Little crystals of garnet occur in some instances (Three Rock Mountain near Dublin). This mineral is found also in the granite of Foxdale in the Isle of Man[3], a closely similar rock, in which the dark mica is very subordinate to the white. Another well-known microcline-bearing rock is the 'grey Aberdeen granite' of Rubislaw[4], *etc.* Similar rocks are found in Donegal.

Among American muscovite-granites may be mentioned those of Concord and Haberville, N.H., and the porphyritic granite of Coanicut Island, R.I.[5] Others occur in Maine, Vermont, and Connecticut.

Rocks in which muscovite is only sparingly or occasionally present form a link with the next division. The Skiddaw granite is of this character[6]. Here the quartz is in great part of prior crystallization to the orthoclase, or there may be some micrographic intergrowth of the two minerals. Felspar-quartz-rocks free from mica are found among the pre-Cambrian intrusions of Ercal in the Wrekin district and of the Malverns. Here too the quartz has crystallized, or has finished crystallizing, before the dominant felspar, which is often microcline. These rocks seem to have affinities with the pegmatites.

The commonest division of the granite family is perhaps *biotite-granite* (Fr. granite, Ger. Granitit), characterized by

[1] Sollas, *Trans. Roy. Ir. Acad.* (1891) xxix, 427–512; *Pr. Geol. Ass.* (1893) xiii, 106; Watts, *Guide*, 31–33.

[2] O'Reilly, *Sci. Pr. Roy. Dub. Soc.* (1879) ii, 246–248, pl. xv.

[3] *Naturalist*, 1894, 68; *Q. J. G. S.* (1895) li, 143.

[4] Adye's *Stud. Micropetr.* 1–4, pl. I, fig. 1.

[5] Pirsson, *A. J. S.* (1893) xlvi, 372, 373.

[6] *Q. J. G. S.* (1895) li, 140.

containing a brown mica to the exclusion of muscovite, hornblende, or augite. Such a rock may consist, *e.g.*, of orthoclase, albite or oligoclase, quartz, biotite, and minor accessories, with the normal order of crystallization.

The relative proportions of the several minerals vary considerably. In the granites (Ordovician and some older) of Wales[1] quartz is very abundant, and biotite (often chloritized) is only sparingly found. The dominant felspar is often a plagioclase (Caernarvon, St David's, *etc.*), and probably some of these rocks would be placed among the 'soda-granites' of certain authors. The St David's rock shows a strong tendency to the micrographic structure.

Biotite-granites of Upper Palæozoic age (Old Red Sandstone) are extensively developed in the Cairngorm[2] and Monadhliath Mts and other parts of the Scottish Highlands. In many British examples microcline partly or wholly takes the place of orthoclase (Malvern, Ross of Mull, Peterhead, *etc.*). Albite-veins intergrown in both orthoclase and microcline may sometimes be observed, *e.g.* in the Eskdale granite of Cumberland. In this rock the quartz is either intergrown in micrographic fashion with the orthoclase, or has crystallized before it. The latter is the case too in the well known porphyritic granite of Shap in Westmorland[3] (fig. 7, *A*), which is further noteworthy for its abundant sphene.

Both micrographic and miarolitic structures characterize the Tertiary biotite-granites of the Mourne Mts, Carlingford[4], and Arran[5], the crystals on the walls of the druses presenting very perfect crystal boundaries. Microperthitic structure is very prevalent in the felspar of the Arran granites.

Biotite-granites are of wide-spread occurrence in the Atlantic States of America[6], as well as in Nova Scotia and

[1] *Q. J. G. S.* (1888) xliv, 444, 445, and *Bala Volc. Ser. Caern.* 59, 61 (Sarn); Geikie, *Q. J. G. S.* (1883) xxxix, 314, pl. x, fig. 11 (St David's); Jennings and Williams, *ibid.* (1891) xlvii, 380 (Ffestiniog).

[2] Craig, *Summary of Progress Geol. Sur.* 1898, 28, and 1900, 22.

[3] Teall, pl. xxxv, fig. 1 [395]; Harker and Marr, *Q. J. G. S.* (1891) xlvii, 275–285, pl. xi, fig. 1; Adye's *Stud. Micropetr.* 13, 14, pl. iii, fig. 1.

[4] Sollas, *Trans. Roy. Ir. Acad.* (1894) xxx, 490.

[5] *Geol. N. Arran, Mem. Geol. Sur. Scot.* (1903) 104, 105.

[6] Kemp, *Bull. Geol. Soc. Amer.* (1899) x, 377–382.

New Brunswick. In Maine five-sixths of the granitic rocks belong to this division. Several varieties are described by Kemp from Rhode Island and Connecticut, some containing allanite (Westerly), garnet (Stony Creek), and other special minerals. In some of these rocks microcline is a prominent constituent, as also in biotite-granites from Central Maryland[1] and Alabama[2]. The granite of Ilchester, Md.[3], contains primary epidote, with allanite; but the abundant epidote which is the characteristic of the Unaka type[4] in the Great Smoky Mts of North Carolina and Tenessee seems to be wholly secondary,

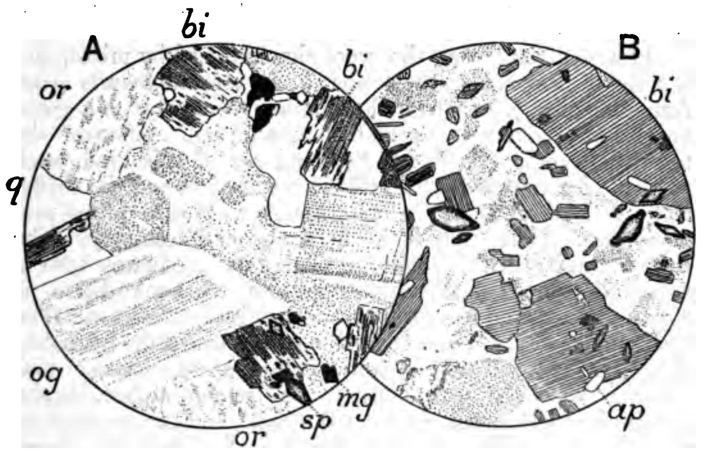

FIG. 7. BIOTITE-GRANITE, SHAP FELL, WESTMORLAND; × 20.

A. The normal rock; showing apatite, sphene (*sp*), magnetite (*mg*), biotite (*bi*) partly chloritized, oligoclase (*og*), orthoclase (*or*), and quartz (*q*) [395 *a*].

B. Dark basic secretion in the foregoing; of finer texture and richer in biotite, sphene, and apatite [1069].

[1] Keyes, *15th Ann. Rep. U. S. G. S.* (1895) 696–730.
[2] Clements, *Bull.* 5 *Geol. Sur. Ala.* (1896) 139–142; Brooke, *ibid.* 185, 186.
[3] Hobbs, *A. J. S.* (1899) xxxiii, 223–228.
[4] Bradley, *A. J. S.* (1874) vii, 519, 520; Watson, *Journ. Geol.* (1904) xii, 395–398.

from reactions between the plagioclase and biotite. Coarse-grained porphyritic biotite-granites are extensively developed in Georgia[1], and similar rocks occur in North[2] and South Carolina. The potash-felspar is orthoclase or microcline in various proportions, while oligoclase (or sometimes albite) is also well represented.

Rocks belonging to this division cover large areas in South Africa. The coarse biotite-granite of the neighbourhood of Capetown is an example. The granite of the Matopo Hills is rich in microcline. In Northern Rhodesia Mennell[3] has found primary epidote and allanite as frequent accessory constituents.

Less abundant than the types characterized by micas, and usually of less acid composition, is *hornblende-granite* (Ger. Amphibolgranit), in which the distinctive mineral is a green hornblende, usually with biotite in addition. Some of the newer Palæozoic granites of Scotland are of this kind, such as that of Lairg[4] and Ord Hill[5] in Sutherland and the Criffel rock at Dalbeattie[6] in which, however, biotite often predominates. Here allanite is an occasional accessory. The Criffel granite, with others in Galloway, graduates into a quartz-diorite. The hornblende-granite of Loch Etive is coarse-grained, and has porphyritic crystals of orthoclase. The rock quarried at Mount Sorrel near Charnwood, Leicestershire[7], is also in part a hornblende-granite, having that mineral associated with biotite. In Ireland a hornblende-granite has been described from Donegal[8], and others occur in the Newry district. These latter are of a relatively basic

[1] Watson, *Journ. Geol.* (1901) ix, 97–122; *Bull. No.* 9 *A*, *Geol. Sur. Ga.* (1902) pp. 125 *etc.*

[2] Watson, *ibid.* (1904) xii, 383–401.

[3] *G. M.* 1902, 362, and 1903, 345–347.

[4] Heddle, *M. M.* (1883) v, 178–184; Cole's *Stud. Micro. Sci.* No. 42 (plate); McMahon, *G. M.* 1899, 194–196.

[5] Cole's *Stud. Micro. Sci.* No. 38 (plate).

[6] Teall, *Mem. Geol. Sur. Scot.*, *Expl. Sheet* 5 (1896) 41–43; *Ann. Rep. Geol. Sur.* for 1896, 41–44; and *Mem. Geol. Sur.*, *Silur. Rocks Scot.* (1899) 507–525.

[7] Bonney, *Q. J. G. S.* (1878) xxxiv, 219; *20th Cent. Atlas*, p. 38 and plate.

[8] Hatch, *Q. J. G. S.* (1888) xliv, 548–551.

type, rich in hornblende and biotite, and their characters remove them from the ordinary granites.

Hornblende-granites are a common type among the Tertiary intrusions of Skye[1], Rum, and Mull. In some the brownish green hornblende is associated with subordinate biotite. The rocks often show a rude micrographic structure and graduate into typical granophyres, in which the biotite, and to some extent the hornblende, give place to a greenish augite. A miarolitic structure is common, the cavities often obscured by secondary products.

Hornblende-granites, often rich in sphene, are largely developed in Nevada and Utah. In Massachusetts the Rockport granite is a well-known example; that of Cape Ann has subordinate augite with the hornblende and biotite, and allanite as an accessory[2]; that of Quincy has instead of hornblende the deep blue amphibole-mineral riebeckite[3], which has also been described by Lacroix from St Peter's Dome, El Paso, Colorado. The Albany granite[4], in New Hampshire, carries porphyritic crystals of orthoclase with perthitic intergrowths of albite: Biotite, hornblende, and sometimes pyroxene are present, and zircon is a conspicuous accessory.

Other hornblende-granites have been described from the Transvaal, Rhodesia (Buluwayo), Victoria[5], New South Wales[6] (south coast), and Queensland[7].

If we exclude the granophyric varieties, *augite-granite* is by no means an abundant rock-type. An example, of Old Red Sandstone age, occurs in the Cheviots[8]. This consists of orthoclase, plagioclase, quartz, augite, exceptionally enstatite, biotite, iron-ores, and apatite, the quartz and orthoclase sometimes showing a micrographic intergrowth. The rock

[1] *Tertiary Igneous Rocks of Skye*, *Mem. Geol. Sur.* (1904) chap x.
[2] Iddings, in Diller, 179, 180.
[3] Washington, *A. J. S.* (1898) vi, 180, 181.
[4] Hawes, *A. J. S.* (1881) xxi, 23.
[5] Howitt, *Tr. Roy. Soc. Vict.* (1880) xvi, 45 (Swift's Creek).
[6] Curran, *Journ. Roy. Soc. N. S. W.* (1891) xxv, 214–217; Anderson, *Rec. Geol. Sur. N. S. W.* (1892) ii, 144–149.
[7] Curran, *loc. cit.* 217, 218 (Burdekin River).
[8] Teall, pl. xxxix, fig. 2, and *G. M.* 1885, 112–116; Kynaston, *Tr. Edin. G. S.* (1899) vii, 390–397.

represents one of the most basic types of the granite family. In some of the granites, graduating into granophyres, of Mull and the Red Hills of Skye augite is the dominant coloured mineral, but it tends to be converted to hornblende, and primary hornblende often accompanies it. A typical augite-granite is found at Loch Ba, Mull (fig. 8, *A*).

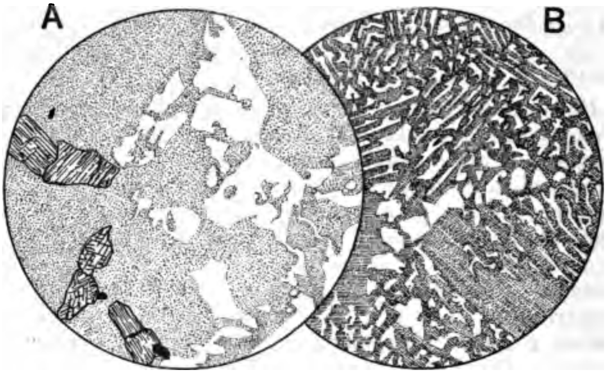

FIG. 8. MICROGRAPHIC INTERGROWTH OF FELSPAR (TURBID) AND QUARTZ (CLEAR); × 20.

A. Rude type of intergrowth in augite-granite, Loch Ba, Mull [4883].

B. More delicate structure in granite (granophyre) of Beinn Dearg Mhòr, Skye [2327].

Augite-granites with anorthoclase as the dominant felspar ('soda-granites') are described from Minnesota[1], New Brunswick[2], and other parts of North America. These rocks also tend strongly to micrographic structures, and graduate into typical granophyres. In an augite-granite from Buluwayo, Rhodesia[3], the felspar is a microperthitic intergrowth of microcline and oligoclase. Another occurrence is at Mt Dromedary on the south coast of New South Wales[4].

[1] Grant, 21*st Ann. Rep. Geol. Sur. Minn.* (1894) and *Amer. Geol.* (1893) xi, 383–388.

[2] Mathew, *Tr. N. Y. Acad. Sci.* (1895) xiv, 204–208, pl. XVI, XVII.

[3] Mennell, *The Geology of S. Rhodesia* (1904) 30, 31.

[4] Anderson, *Rec. Geol. Sur. N. S. W.* (1892) ii, 148.

In Southern India a peculiar *hypersthene-granite* is of wide-spread occurrence, and has been described by Mr Holland[1] under the name charnockite. The typical rock consists of quartz and potash-felspar, with oligoclase, hypersthene, opaque iron-ore, and a little zircon, often with the addition of garnet. The dominant felspar seems to be microcline, often with parallel microperthitic intergrowths of plagioclase. The rock frequently shows some gneissic banding.

Closely related to the granites is the rock known as *aplite* (granite-aplite). It occurs as veins in granite, but cutting the latter and traversing adjacent rocks, and by some petrologists it would be placed in the hypabyssal division. It is a fine-textured rock with 'panidiomorphic' to granulitic structure, and is somewhat more acid than the associated granite. A characteristic type occurs in connection with the muscovite-granites near Dublin (fig. 6, *B*). It consists of microcline, with some oligoclase, quartz, muscovite, and red garnet. An aplite at Meldon in Devonshire[2] is of similar character, but instead of garnet contains topaz and some colourless or pale tourmaline. The Crosby dyke[3] in the Isle of Man may be referred here.

Washington[4] has described aplite dykes cutting the granite of Essex Co., Mass., and Pirsson notes aplites on Coanicut Island, R.I. In the Sierra Nevada region Turner[5] has remarked dykes of soda-aplite, consisting essentially of albite and quartz with sometimes muscovite, besides other aplites in which a potash-felspar is the dominant one. Aplite dykes are associated with the muscovite-granite of Stone Mt, Georgia[6]. Various examples have been described from Australia, *e.g.* from Dargo, Victoria[7].

The *pegmatites* belonging to this family of rocks (granite-pegmatites) consist essentially of microcline or orthoclase and quartz, often with white mica and sometimes red garnet. The

1 *Mem. Geol. Sur. Ind.* (1900) xxviii, 134–141.
2 Teall, p. 316; McMahon, *G. M.* 1901, 316–319.
3 Hobson, *Q. J. G. S.* (1891) xlvii, 440.
4 *Journ. Geol.* (1899) vii, 105, 106.
5 *Ibid.* 156–158.
6 Watson, *ibid.* (1902) x, 186, 187.
7 Howitt, *Tr. Roy. Soc. Vict.* (1887) xxiii, 135, 136.

texture is often extremely coarse, and there is a frequent tendency to the graphic structure. Such rocks are extensively developed in connection with the Archæan gneiss of Sutherland. Others occur in Forfarshire[1]: these are rich in muscovite, and locally carry garnet or tourmaline. It may be observed that these British pegmatites are not rich in rare or special minerals. In the United States, on the other hand, many of the most noted mineral-localities are furnished by pegmatites of this kind; *e.g.* Stoneham and Hebron in Maine, Chesterfield in Massachusetts, Haddam in Connecticut, Pike's Peak in Colorado, and Harney's Peak in the Black Hills of Dakota.

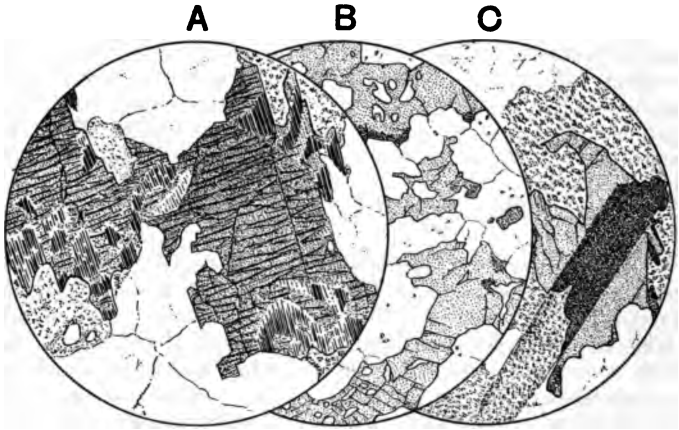

FIG. 9. TOURMALINIZATION OF GRANITES; × 20.

A. Conversion of biotite to brown tourmaline, Busava, Cornwall. The other constituents are much-decomposed felspar and clear quartz [3949].

B. Final result of change, schorl-rock, Sheep Tor, Dartmoor. The rock consists wholly of tourmaline (brown with patches of blue) and clear quartz, largely of new formation [4253].

C. Tourmaline-Granite, Ivybridge, Dartmoor. Tourmaline replacing a felspar crystal is deep blue, while the rest of the same crystal of tourmaline is brown [3950].

[1] Barrow, *G. M.* 1892, 64; *Q. J. G. S.* (1893) xlix, 332–336.

Central Maryland is another district[1]. Pegmatitic and aplitic dykes, both carrying red garnet, occur in the Montara granite of San Francisco[2], and such dykes, with only a small quantity of mica, are associated with the Santa Lucia granite near Monterey[3].

The *tourmaline-granites* appear as modifications of more normal granitic rocks. The tourmaline seems to take the place of the mica (fig. 9, *A*). As a further modification, the felspars may be replaced partly or wholly by tourmaline and quartz, the former sometimes occurring in little needles with radiate grouping embedded in clear quartz. The extreme modification is a tourmaline-quartz-rock or *schorl-rock* (fig. 9, *B*), in which felspar is wholly wanting, while tourmaline may occur in two or more habits, as crystals or grains and as groups of needles. All these types are illustrated among the Cornish[4] and Dartmoor granites. A curious variety known as luxulyanite has been described by Dr Bonney[5] (fig. 10, *A*). Here the conversion of felspars into clear quartz, crowded with radiate groups of tourmaline needles, can be traced in various stages, the little needles, about ·03 inch in length, giving pale brown and light indigo colours for longitudinal and transverse vibrations respectively, while a brown tourmaline in distinct grains has been supposed to represent the mica of the granite. In general a blue colour seems to characterize especially tourmaline which replaces felspar (fig. 9, *C*). A schorl-rock from Trowlesworthy Tor contains fluor[6].

The rock known as *greisen* (hyalomicte of French writers) consists essentially of quartz and white mica, which seems to be often a lithia-bearing variety. The Cornish greisens[7] are

[1] G. H. Williams, *15th Ann. Rep. U. S. Geol. Sur.* (1895) 675–684.

[2] Lawson, *ibid.* 413.

[3] Lawson, *Bull. Dep. Geol. Univ. Cal.* (1893) i, 16, 17.

[4] For figures of Cornish tourmaline-granites, see Cohen (3), pl. XXII, fig. 2; *20th Cent. Atlas*, 35, 59, with plates.

[5] *M. M.* (1877) i, 215–222; Semmons, *Pr. Liverp. G. S.* (1878) iii, 357, 358.

[6] Worth and Bonney, *Trans. Roy. Geol. Soc. Cornw.* (1884) x, 177–188.

[7] Teall, 315 (St Michael's Mount); Scrivenor, *Q. J. G. S.* (1903) lix, 149–158 (Cligga Head).

apparently a modification of the granite in the same sense as the tourmaline-rocks are, but with a different result. The place of the felspar is taken by mica and topaz, though tourmaline is also met with. Closely connected with the greisens, and, like them, developed usually along joint-planes in the granite, are *tinstone-veins.* Here cassiterite is the characteristic mineral, associated with topaz, white mica, quartz, etc., and often a little brown tourmaline, derived from the biotite of the granite (fig. 10, *B*).

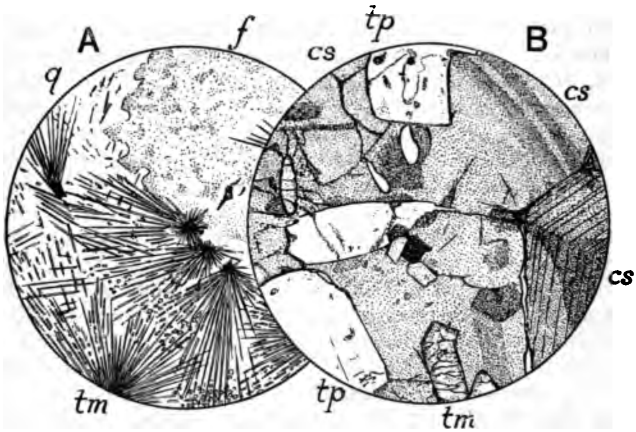

FIG. 10. PNEUMATOLYTIC MODIFICATIONS OF GRANITE, CORNWALL; × 20.

A. Schorl-rock (luxulyanite); showing replacement of felspar (*f*) by clear quartz (*q*) and radiating needles of blue tourmaline (*tm*) [4079].

B. Tinstone vein, Single Rose. The cassiterite (*cs*) varies in colour, partly in concentric zones: one crystal shows the prismatic cleavage and the twinning on the dome plane. The other constituents are clear topaz (*tp*) and small crystals of tourmaline (*tm*) [4251].

In conclusion we will note some examples of the dark, fine-grained, ovoid patches frequently enclosed in granitic rocks, and regarded as *basic secretions* separated out from the granite-magma at an early stage, not necessarily *in situ.* Mr J. A. Phillips[1] described such patches from the muscovite-granites

[1] *Q. J. G. S.* (1880) xxxvi, 1–21; (1882) xxxviii, 216, 217.

of Gready in Cornwall and Foggen Tor on Dartmoor and the biotite-granites of Shap and Peterhead, and he distinguished them from foreign fragments caught up and metamorphosed by the magma. The characteristic of the true secretions is that they consist of the same minerals as the enveloping rock, but contain the earliest products of crystallization—such as apatite, magnetite, and sphene—in larger proportions, and are also richer in the ferro-magnesian relatively to the felspathic elements of the rock. Sometimes, as in the Criffel granite[1], we may observe that hornblende is more plentiful as compared with biotite than in the normal rock, and similarly plagioclase felspar is more abundant relatively to orthoclase. The numerous dark patches in the Shap granite[2], rich in sphene and biotite (fig. 7, *B*), enclose, like the normal rock, large porphyritic crystals of orthoclase; but these are partially rounded and corroded, the margin of each crystal being replaced by plagioclase and quartz.

Among American rocks good illustrations are afforded by the hornblende-granite of the Wahsatch Range (Little Cottonwood Cañon, Utah), that of Essex County, Mass.[3], and the biotite-granite of Mount Ascutney, Vt.[4]

Gneisses. The term 'gneiss' is now used to denote, not a rock of some defined composition, but any crystalline rock possessing a *gneissic structure*. By this is to be understood a banded or streaky character due to the association or alternation of different lithological types in one rock-mass, or to the occurrence of bands or lenticles specially rich in some particular constituent of the rock. The structure is often found on a relatively coarse scale in rocks of granitoid texture, so that it is to be observed rather in the field or in large specimens than in microscopical preparations. It may, however, be associated with foliation on a smaller scale or with a partial parallel disposition of the elements of the rock. Gneisses, in this sense, may have the chemical and mineralogical composition of acid

[1] Teall, *Mem. Geol. Sur. Scot., Expl. of Sheet* 5 (1896) 42.

[2] *Q. J. G. S.* (1891) xlvii, 281, 282, pl. XI, fig. 2; Adye's *Stud. Micropetr.* 15, 16, pl. III, fig. 2.

[3] Washington, *Journ. Geol.* (1898) vi, 795.

[4] Jagger, *Bull.* 148 *U. S. G. S.* (1897) 68.

or intermediate or basic rocks, or may belong to types without parallel among the known products of igneous magmas.

It is generally recognized that gneisses as thus defined have originated in more than one way, although difference of opinion exists as to the interpretation of the facts in particular districts. There are (i) gneisses in which the banded arrangement, as well as the mineralogical constitution, of the rock-masses is directly connected with an igneous origin; (ii) gneisses which represent the extreme phase of thermal metamorphism of sedimentary strata, the banding being the result of lithological differences between successive beds and seams in the original sediments; and (iii) gneisses which result from the bodily deformation of rock-masses, especially plutonic rocks, under the operation of powerful mechanical forces, the banding in this case standing in relation to the manner in which those forces have been applied. We are concerned in this place only with the first category: the other two will be dealt with in Chapters XX and XXI, respectively.

In what may be distinguished as *primary igneous gneisses*, then, the banding is to be regarded as an original character of plutonic rocks, dating from the time when the rock in question was still fluid or partly fluid, and due to the different portions of a heterogeneous magma being drawn out in a flowing movement. Under this head, by general assent, are ranked the Lewisian gneisses of the North-West Highlands of Scotland. These rocks, apart from the innumerable dykes by which they are traversed, present much variation in character[1]. In the north, between Cape Wrath and Loch Laxford, hornblendic and micaceous gneisses predominate. From Scourie to beyond Lochinver and Loch Assynt the prevalent type is a pyroxenic gneiss, consisting essentially of augite or hypersthene (Kylesku), felspars, and quartz. There are also acid types, consisting mainly of felspars and quartz; while, on the other hand, the dominant rock encloses portions very rich in green hornblende. Hornblendic and micaceous gneisses predominate again about

[1] Teall, *Ann. Rep. Geol. Sur.* for 1894, 280, 281. For a fuller account see *The Geological Structure of the North-West Highlands*, *Mem. Geol. Sur.* (1907). The greater part of the area (in Lewis itself) is still unsurveyed. On the petrography of Lewisian inliers in Rossshire, see Flett, *Summary of Progress Geol. Sur.* for 1905, 158–160.

Gairloch and Loch Torridon, and a coarse hornblendic gneiss occurs in Lewis (Stornoway) besides other types. Many of these rocks show in varying degree the effects of dynamic metamorphism, but it is certain that much of the banding (as distinguished from foliation) may be ascribed to original conditions attending the intrusion of igneous magmas[1].

Again, it has been shown that the great bulk of the Laurentian gneisses, in Canada, consists of plutonic rocks, in which the banding is a primary flow-structure. In the Rainy Lake region Lawson[2] found granites and syenites to be the prevalent types. Gen. McMahon[3] assigned the gneissic granites of the Himalayas to a like origin.

In the South Indian 'charnockites' (pyroxene-gneisses or pyroxene-granulites of some authors), already referred to under the head of hypersthene-granite, Mr Holland has shown that the frequent banding and foliation are primary, but dynamic effects are also indicated, notably in the production of garnet. Lacroix[4] noted that in these rocks the felspars are often crowded with little round or elongated inclusions of quartz ('quartz de corrosion' of French writers) without the regularity of a graphic intergrowth. This is ascribed to secondary corrosion.

In the South-Eastern Highlands (Forfarshire and Kincardineshire) Mr Barrow[5] has described certain micaceous gneisses which are clearly igneous intrusions separable from the metamorphic gneisses, with which they are associated. In one phase the rocks consist essentially of quartz, peculiar rounded crystals of oligoclase, muscovite, and biotite. Another phase shows abundant microcline, with a corresponding diminution of oligoclase, while at the same time the white mica predominates increasingly over the brown, and builds larger crystals. The author makes it clear that the remarkable features of these igneous gneisses are due in the main to crust-movements at the epoch of intrusion.

[1] Geikie and Teall, *Q. J. G. S.* (1894) l, 657–659.
[2] *Rep. Geol. Sur. Can.* (1888) 112 F–142 F.
[3] *G. M.*, 1887, 212–220; 1888, 61–65.
[4] *Rec. Geol. Sur. Ind.* (1891) xxiv, 157–190.
[5] *G. M.* 1892, 64, 65; *Q. J. G. S.* (1893) xlix, 330–335.

It is to be noted that the setting up of gneissic banding as a primary character in a plutonic rock implies two conditions, *viz.* a heterogeneous constitution of the mass and a differential movement of the nature of flowing. The heterogeneity may arise from imperfect differentiation or from imperfect admixture of two magmas or of an igneous magma with partially dissolved enclosed material. A good example, in which the requisite heterogeneity arose from an incomplete admixture of partially dissolved basic rock (eucrite) in a granite magma, is afforded by the Tertiary gneisses of the Isle of Rum[1]. In other cases as in the Rainy Lake region, the inclusion of solid fragments, which become oriented and alligned by the fluxional movement, may be found as a subsidiary feature, emphasizing further any more or less pronounced banding.

[1] *Q. J. G. S.* (1903) lix, 207–213; *Tr. Edin. Geol. Soc.* (1905) viii, 346–348; *Geol. of Small Isles*, *Mem. Geol. Sur.*, chap. IX.

CHAPTER III.

SYENITES (*including* NEPHELINE-SYENITES).

THE syenites are even-grained, holocrystalline rocks consisting essentially of alkali-felspars, and in one group felspathoid minerals, with ferro-magnesian constituents, typically in smaller proportion, and various minor accessories. The texture is often rather coarse to medium-grained, and the structure is that characteristic of plutonic rocks, the several minerals following the normal order of crystallization, and most of them having only imperfect crystal outlines (hypidiomorphic structure of Rosenbusch). In many syenites, however, the order of crystallization is modified by simultaneous intergrowths of different minerals.

This family of rocks is less widely distributed and less abundant than the granites. Considered from a chemical point of view, it is characterized by an unusually high percentage of alkalies. In the syenites which depart farthest in this respect from the commoner types of igneous rocks, the character shows itself in the presence of felspathoid constituents and soda-bearing ferro-magnesian minerals.

The type characterized by hornblende and alkali-felspars is known as 'syenite proper'[1], or, for clearness, *hornblende-syenite*. When biotite more or less completely takes the place of hornblende, we have *mica-syenite*; and when augite occurs prominently, often in company with one or both of the other

[1] The original syenite of Werner was the hornblende-granite of Syene or Assouan on the Nile. The name, however, has come to be universally applied to the family under notice, rocks often hornblendic but typically free from quartz.

coloured minerals, *augite-syenite*. The group characterized by the occurrence of nepheline or sodalite in addition to felspar is named *nepheline-syenite*, or often elæolite-syenite, without distinction according to the dominant ferro-magnesian constituent, though several types, mostly of restricted occurrence, have received special names. A *leucite-syenite* is known only in the form of rocks with pseudomorphs of orthoclase, nepheline, muscovite, *etc.*, in the shape of leucite (fig. 15).

The occurrence of subordinate quartz in some syenites gives rise to the varieties *quartz-syenite*, *quartz-mica-syenite*, and *quartz-augite-syenite*, but free silica never occurs in the nepheline-bearing group. On the other hand the coming in of a lime-soda-felspar as a prominent constituent in addition to the alkali-felspar gives rise to types intermediate between true syenites and diorites, and to these the name *monzonite* is sometimes given. This name was originally given to a particular type from the Monzoni district, in the Tirol, but has been employed by Brögger in a wider sense. This geologist has constituted a separate family to include those plutonic rocks in which orthoclase and a plagioclase felspar are represented in approximately equal proportions. It embraces quartz-monzonites at the one end and thoroughly basic types at the other.

Constituent Minerals. In mode of occurrence, inclusions, alteration-products, *etc.*, the felspars of syenites resemble those of granites. Besides *orthoclase*, *microcline*, and *albite* or *oligoclase*, there occur, especially in the augite- and nepheline-syenites, felspars rich in both potash and soda, known as soda-orthoclase, soda-microcline, anorthoclase, *etc.* These are regarded by some mineralogists as intergrowths on an ultra-microscopic scale of a potash- and a soda-felspar (*cryptoperthite*). An evident parallel intergrowth of albite and microcline or albite and orthoclase (*microperthite*) is also frequent in the same rocks.

When nepheline occurs, it is usually of the variety known as *elæolite*, in larger and less perfect crystals than the nepheline of volcanic rocks. If idiomorphic, it forms hexagonal prisms with the basal plane bevelled by narrow pyramid-faces. In more shapeless crystals the straight extinction can be verified

by reference to rows of inclusions which follow the direction of the vertical axis, and seem to determine the alteration of the mineral. The elæolite is colourless or often rather turbid. It gives rise by decomposition to various soda-zeolites or to moderately brightly polarizing prisms, fibres, and aggregates of cancrinite. A frequent associate of elæolite is *sodalite,* in dodecahedra or in allotriomorphic crystal-plates and wedges. It is colourless or faint blue in slices, and is easily recognized by its isotropic behaviour. It encloses fluid-pores, microlites of ægirine, *etc.*, and secondary products similar to those of elæolite.

The common *hornblende* of syenites is partly idiomorphic but without terminal planes. It is of the green pleochroic variety, giving in vertical sections a maximum extinction-angle of 12° to 16°. Its inclusions and alteration-products are the same as in granite. Some augite-syenites contain the soda-amphibole *barkevicite* with intense brown absorption and pleochroism and an extinction-angle of about 12°.

The *augite,* when it occurs as an accessory, is colourless or very pale green, with the same properties as in granite. In the augite-syenites it is sometimes pale green with faint pleochroism, sometimes pale brown to violet-brown with very distinct pleochroism. Various types of schiller- and diallage-structures are sometimes seen, and may affect only a portion—usually the interior—of a crystal (fig. 12). A green pleochroic *ægirine* occurs in some augite-syenites and many nepheline-syenites, and intergrowths of this with augite are not uncommon.

The *biotite* of the syenites is deep brown, becoming green only by secondary changes. In some augite- and nepheline-syenites vibrations parallel to the cleavage-traces are almost completely absorbed. The mineral is roughly idiomorphic, except when intergrown with hornblende or augite.

When *quartz* occurs, it has the same characters as in granite, but is never very abundant. It does not occur in the nepheline-syenites and their allies. Most syenites contain plenty of *sphene* in good crystals showing the cleavages and often the characteristic twinning. *Zircon* is common in small prisms with pyramidal terminations, as in the granites. In

4—2

some of the augite-syenites, however, it builds large crystals of simple pyramidal form. It is easily identified by its limpid appearance and extremely high refringence and birefringence. *Apatite* in colourless needles is widely distributed in syenites. The iron-ores are variable in quantity: they include *magnetite*, *ilmenite*, and *hæmatite*, the last two often in thin flakes enclosed in the felspars. An occasional accessory is *perofskite* in small octahedra, distinguished by their very high refractive index and feeble double refraction. Special types contain *melanite* garnet, brown in slices and always isotropic.

Structure. The texture of the syenites and the mutual relations of their constituent minerals are normally similar to those observed in the granites, Rosenbusch's 'order of consolidation' being, as a rule, followed. In the typical hornblende-syenites there are few peculiarities. When quartz enters, it may be intergrown in micrographic fashion with part of the orthoclase, and this is specially the case in some augite-syenites. When plagioclase felspar is abundant, it is sometimes embraced by shapeless plates of orthoclase, and in the same rocks reversals of order between the bisilicates and the felspars may often be noticed.

Where the felspathoids occur, their place in the order of crystallization is a variable one. These minerals usually precede the felspars, but may continue to crystallize to a later stage. The nepheline-syenites not infrequently take on a porphyritic character: often too a 'trachytic' structure, marked by a partial parallelism of felspars with tabular habit[1].

Some syenites contain basic secretions, acid veins, pegmatite fringes and other peculiarities noticed under the granites. Parallel and gneissic structures sometimes come in locally.

Leading types. Syenitic rocks are but little developed in the British Isles. The name 'syenite' as found in many of the earlier writings and maps in this country is to be understood in the old sense of hornblende-granite (including also granophyre, *etc.*) and the identification of hornblende is in very

[1] Brögger applies the name 'foyaite' to rocks with this structure and 'ditroite' to the granitoid nepheline-syenites, but these terms have by priority different significations.

many cases erroneous. For example, the so-called 'syenites' of St David's, of Ennerdale, of Carrock Fell, *etc.*, have no claim to the title, whether the word be used in its original or its modern sense.

A well-known *quartz-syenite* (Nordmark type) has been described by Brögger from the Christiania district. It has oligoclase in addition to the dominant orthoclase, and sometimes a microperthitic intergrowth of albite and orthoclase. Biotite and hornblende are the chief ferro-magnesian constituents, but green augite, arfvedsonite, and ægirine also occur. This type is known in America, *e.g.* in the Montreal district[1]. In Sutherland the large intrusive mass of Cnoc na Srôine[2], near Loch Borolan, consists mainly of a quartz-syenite approximating to the Nordmark type; but it graduates on the one hand into granite and on the other into quartzless syenite, often containing melanite, and other more remarkable types.

Some quartz-syenites containing augite show a strong tendency to micrographic intergrowth of quartz and felspar. This is seen in the larger pre-Carboniferous intrusions of Leicestershire (excepting the Mount Sorrel granite), which indeed may be classed as a less acid type of granophyre. The augite tends to pass into uralitic hornblende, and epidote is a characteristic secondary product in the rocks. Examples are seen at Groby, Bradgate Park, Markfield, and Garendon, all in the Charnwood Forest district[3].

The rock taken as the type of *hornblende-syenite* is that of Plauen'scher Grund near Dresden (fig. 11). It is composed essentially of soda-orthoclase[4], with only subordinate oligoclase, and green hornblende. Apatite, magnetite, and sphene occur as accessories, and in places a little quartz. There is a variety in which biotite occurs in addition to the hornblende. The rock encloses dark basic secretions richer in plagioclase, hornblende, apatite, magnetite, and sphene.

A syenite like that of Dresden, but sometimes rich in biotite, occurs near Salem, Mass.[5] More felspathic varieties

[1] Dresser, *Amer. Geol.* (1901) xxviii, 207, 208 (Shefford Mt).
[2] Teall, *G. M.* 1900, 385–392.
[3] Bonney, *Q. J. G. S.* (1878) xxxiv, 214–218.
[4] Washington, *A. J. S.* (4) xxii (1906), 129–135.
[5] Wadsworth, *G. M.* 1885, 207.

have been noted from Curtis Point, Beverley, Mass.[1] (with arfvedsonite-like hornblende) and Albany, N. H. (with blue riebeckite).

The *mica-syenite* type, in which biotite predominates over hornblende, is of uncommon occurrence, except as a local variety of hornblende-syenite. Rosenbusch notes examples from Canada; one from Star Hill Mine, Portland West, P. Q., rich in apatite; another from Blessington Mine, Inchinbrooke, P. O., with some augite as well as mica. These rocks are free from quartz or plagioclase. A rock from Three Tops Mt, Donegal, consists of orthoclase, biotite, and augite, with infrequent plagioclase[2].

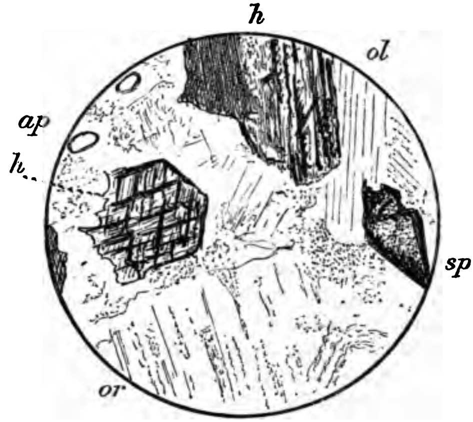

FIG. 11. HORNBLENDE-SYENITE, PLAUEN'SCHER GRUND, DRESDEN; ×20. Showing hornblende (*h*), soda-orthoclase (*or*), subordinate oligoclase (*ol*), sphene (*sp*), and apatite (*ap*) [47].

In the *augite-syenites* in general the pyroxene is associated with more or less biotite or hornblende. A well-known rock of this kind (Larvik type) comes from southern Norway. While augite is usually the dominant ferro-magnesian element, it is often accompanied by biotite, ægirine, hornblende, or

[1] Sears, *Bull. Essex Inst.* (1891) xxiii.

[2] Hyland, *Mem. Geol. Sur. Ire., N.W. and C. Donegal* (1891) 138, 139.

arfvedsonite, and the rock thus passes into mica-syenite, *etc.* Alkali-felspars (orthoclase, microcline, albite, cryptoperthite, *etc.*) make up the bulk of the rock, and are often intergrown with one another. Not infrequently they have a schiller-structure. A little quartz is rarely present; on the other hand elæolite and sometimes olivine may occur as minor accessories. The augite is occasionally green, but commonly light brown with a violet tone and slight pleochroism: schiller-structure is common. The hornblende is green or occasionally brown, the biotite a very deep brown. The latter mineral is roughly idiomorphic, except when it is massed round magnetite or forms a marginal intergrowth with augite. The iron-ores are magnetite and sometimes hæmatite: apatite is universal, but sphene is typically absent. Zircon is a constant accessory, and sometimes builds large crystals, giving the variety 'zircon-syenite' of von Buch and other early writers. These augite-syenites are common as boulders[1] on our east coast (fig. 12).

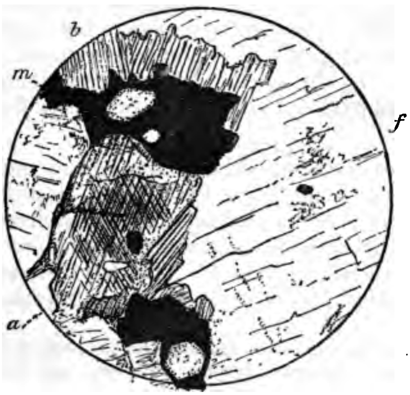

FIG. 12. AUGITE-SYENITE (LARVIK TYPE) FROM A BOULDER ON THE YORKSHIRE COAST; × 20.

The minerals seen are cryptoperthite felspar (*f*) in large plates, augite (*a*) with schiller-structure in the interior of the crystal, deep brown biotite (*b*), magnetite (*m*), and apatite (*ap*) [1841].

[1] *Proc. Yorks. Geol. Pol. Soc.* (1889–90) xi, 303, 304, 410.

Rocks resembling the Larvik type occur near Sivamalai in the Coimbatore district of Madras[1], and again in the Transvaal (Hatherley, near Pretoria)[2]. A biotite-augite-syenite has been described also from Leeuwfontein, in the same district[3]. A rock from Buluwayo[4] is composed of microcline, augite, and hornblende.

Other augite-syenites, rich in microperthitic intergrowths, occur in New Hampshire (Jackson, Stark, and Columbia) and in the Sawtooth Mts of Texas. Examples having ægirine-augite as the dominant coloured silicate come from the Bearpaw Mts in Montana[5] and Mosquez Cañon, Texas, while a more typical *ægirine-syenite* is recorded from Fourche Mt, Arkansas.

The typical *monzonite* of the Tirol is also an augite-bearing rock, and, as already remarked, contains in general a noteworthy amount of plagioclase felspar. This is enclosed, with other minerals, by relatively large crystals of orthoclase (fig. 13, *A*). Biotite is usually present, in flakes sometimes earlier, sometimes later, than the plagioclase. Sphene is frequent, and zircon is often enclosed by the mica. Other constituents are apatite, magnetite, and pyrites, and in some varieties a little interstitial quartz.

In America rocks resembling the typical monzonites have been described from Yogo Peak[6] and Highwood Peak[7] in Montana. These rocks graduate on the one hand into a more felspathic augite-syenite and on the other into a thoroughly basic type very rich in augite. This last (Shonkin type) was first distinguished by the same writers at Square Butte in the

[1] Holland, *Mem. Geol. Sur. India* (1891) xxx, 199–201.

[2] Henderson, *Transvaal Norites, Gabbros, and Pyroxenites* (1898) 46–48.

[3] Hall, *Rep. Geol. Sur. Transv.* for 1903, 38.

[4] Mennell, *G. M.* 1902, 365.

[5] Weed and Pirsson, *A. J. S.* (1896) ii, 136, 137.

[6] Weed and Pirsson, *A. J. S.* (1895) l, 467–479; *20th Ann. Rep. U. S. G. S.* (1900) part III, 475–479.

[7] Pirsson, *Bull.* 237 *U. S. Geol. Sur.* (1905) 76–82. For other American occurrences, see Tower and Smith, *19th Ann. Rep. U. S. G. S.* (1899) part III, 645, 646 (Tintic Mts, Utah); Cross, *21st Rep.* (1900) part II, 79–81 (Rico, Colo.); *etc.*

Highwood Mts, Mont.[1] It consists of predominant augite with orthoclase, albite, and anorthoclase, apatite, biotite, olivine, *etc.*, and may be compared with the basic modifications of the rocks of Monzoni ('pyroxenites' of Brögger).

The 'newer granites' of Scotland, in Argyllshire and in Galloway, sometimes pass into quartz-monzonites and monzonites without quartz. At certain places in Argyllshire, and typically at Kentallen, near Ballachulish, occurs a remarkable basic rock, comparable with the olivine-monzonites of Brögger (Kentallen type)[2]. It consists of olivine, pale green augite, plagioclase, and interstitial biotite and orthoclase. It shows considerable variation, sometimes approximating to the Shonkin type (fig. 13, *B*).

As a connecting link between syenites proper and nepheline-syenites we have the Pulaski type of J. F. Williams[3] from Fourche Mt, near Little Rock, Arkansas, in which nepheline is only an accessory constituent. Various alkali-felspars occur, soda-felspar predominating, and various ferro-magnesian minerals, of which hornblende is the chief. A neighbouring rock, described under the name elæolite-syenite, seems to be not essentially different[4]. The same type occurs, often associated with nepheline-syenites, in other localities, *e.g.* near Montreal[5] and in Essex County, Mass.[6] A syenite with accessory nepheline occurs in the Port Cygnet district, Tasmania[7]. It has the trachytic structure, and consists principally of microperthitic orthoclase with interstitial albite. It is almost free from ferro-magnesian minerals; but augite-syenites are found in the same district, and sometimes contain analcime, perhaps derivative after nepheline.

[1] *Bull. Geol. Soc. Amer.* (1895) vi, 408–415; *cf.* *20th Ann. Rep. U. S. G. S.* (1900) part III, 479–484, pl. LXXII.

[2] Teall, pl. XVI, fig. 1, and *Ann. Rep. Geol. Sur.* for 1896, 22, 23; Hill and Kynaston, *Q. J. G. S.* (1900) lvi, 531–540, pl. XXIX, XXX; Hill, *Summary of Progress Geol. Sur.* for 1899, 48–53. See also *20th Cent. Atlas*, 42, with plate.

[3] *Ign. Rocks of Arkansas*, vol. ii of *Ann. Rep. Geol. Sur. Ark.* for 1890, 55–69; Diller, pp. 194–197.

[4] *Ign. Rocks Ark.* 74–81; Washington, *Journ. Geol.* (1901) ix, 610.

[5] Adams, *Journ. Geol.* (1903) xi, 269–273 (Mt Johnson); Dresser, *Amer. Geol.* (1901) xxviii, 209, 210 (Shefford Mt).

[6] Washington, *Journ. Geol.* (1898) vi, 804–807.

[7] *Proc. Roy. Soc. Tas.* for 1898–9, 21, 22.

The only *nepheline-syenite* known in Britain occurs in association with other syenitic rocks at Cnoc na Srôine in Sutherland. As described by Dr Teall[1], it consists of nepheline and alkali-felspar in about equal amounts with some greenish biotite and melanite garnet.

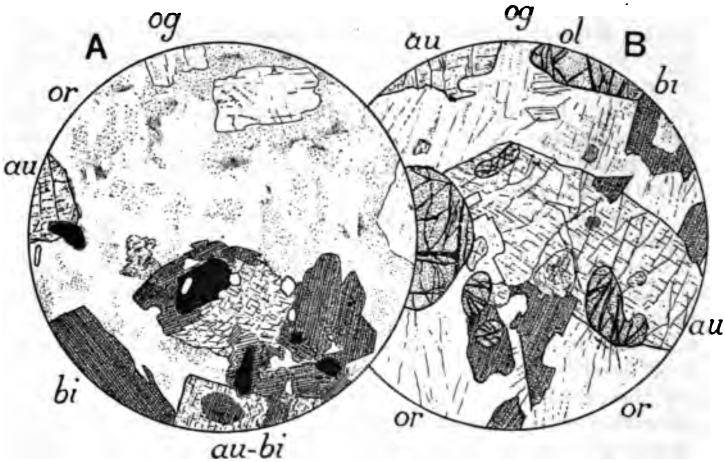

FIG. 13. MONZONITES; ×20.

A. Typical Monzonite, Predazzo, Tirol: showing apatite, magnetite, colourless augite (*au*) and brown biotite (*bi*) sometimes intergrown, oligoclase (*og*), and orthoclase (*or*) [3483].

B. Olivine-Monzonite (Kentallen type), Kentallen, near Ballachulish, Argyllshire. Here the ferro-magnesian minerals are in greater amount, and include abundant olivine (*ol*) [3387].

A well-known nepheline-syenite is that of Sierra de Monchique in Portugal[2] (Foya type). Here the felspar is orthoclase, and is in excess of the nepheline; sodalite is often present; the coloured minerals are subordinate hornblende, augite edged with ægirine-augite, and biotite; while apatite, magnetite, and abundant sphene are also present. Rocks generally comparable with this occur in Brazil, near Montreal

[1] *G. M.* 1900, 387, 388; *The Geological Structure of the North-West Highlands*, *Mem. Geol. Sur.* (1907) 446.

[2] Sheibner, *Q. J. G. S.* (1879) xxxv, 42–47, pl. II.

(with melanite), at Salem and Marblehead[1] (Mass.), in the Crazy Mts (Mont.)[2], at Mt Ord and Paisano Pass (Tex.)[3], and at several localities in Arkansas[4]. Some of the Arkansas rocks have porphyritic modifications. At Beemerville (N.J.)[5], again, occurs a variety with very large crystals of orthoclase.

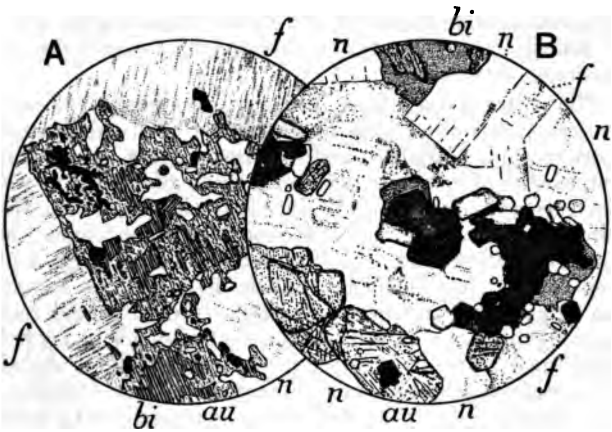

FIG. 14. NEPHELINE-SYENITES, SOUTHERN NORWAY; ×20.

A. Kragerö: showing apatite and magnetite as accessories, brown biotite (*bi*) and green ægirine-augite (*au*) in parallel intergrowth, mirco- and cryptoperthite felspar (*f*), and clear interstitial nepheline (*n*) [4296].

B. Lunde, near Larvik (Lardal type): showing abundant apatite and magnetite, pale augite and brown biotite, idiomorphic nepheline, and cryptoperthite felspar [3391].

[1] Wadsworth, *Proc. Bost. Soc. Nat. Hist.* (1882) xxi, 406; *G. M.* 1885, 208, 209; Sears, *Bull. Essex Inst.* (1893) xxv; Washington, *Journ. Geol.* (1898) vi, 801–804.

[2] Wolff and Tarr, *Bull. Mus. Comp. Zool. Harv.* (1893) xvi, 230, 231.

[3] Osann, *4th Ann. Rep. Geol. Sur. Tex.* (1893) 126–129.

[4] J. F. Williams, *Ign. Rocks Ark.* (1890) 85–87 (Fourche Mt); 132–139 (Saline Co.); 233–238 (Magnet Cove); 349, 350 (Potash Sulphur Springs). On the Magnet Cove (Diamond Jo) rock see also Washington, *Journ. Geol.* (1891) ix, 610, 611.

[5] Emerson, *A. J. S.* (1882) xxiii, 302–308; Kemp, *Trans. N. Y. Acad. Sci.* (1892) xi, 63; Iddings in Diller, 209, 210.

A peculiar rock is found, with other varieties, in southern Norway (Lardal type). It is usually of very coarse texture: a finer kind is represented in fig. 14, *B*. The abundant nepheline is in idiomorphic crystals. There is a considerable variety of alkali-felspars, cryptoperthite predominating. The ferro-magnesian minerals include deep-brown mica and either a greenish ægirine-augite or the violet-brown augite noted in the Larvik rock. Apatite is abundant, and olivine is an occasional constituent.

The Ditro type[1], from Transylvania, carries mica, but not very plentifully: it is distinguished by its abundance of allotriomorphic sodalite and by the variety and intimate intergrowths of its felspars, which include microcline as well as orthoclase and oligoclase. In the Litchfield type[2], from Maine, albite constitutes about half of the rock, the other minerals being orthoclase, microcline, elæolite, sodalite, cancrinite, a deep green biotite (lepidomelane), and a little zircon. A variety from Dungannon[3] in Ontario resembles the Litchfield rock in the predominance of a soda-felspar, but is richer in nepheline. Nepheline-syenites, graduating into syenites without nepheline, have a wide distribution in that part of eastern Ontario, and are of special interest as containing corundum as a primary constituent[4]. Characteristic nepheline-syenite is known in New South Wales (Kiama district)[5].

Among other varieties in the interesting syenitic complex of western Sutherland is one which may be styled a *leucite-syenite* (Borolan type)[6]. It is exposed near Loch Borolan. The rock consists essentially of orthoclase, a brown melanite garnet, and a green or green-brown biotite. A green monoclinic pyroxene is present in many examples: a brown pleochroic sphene,

[1] For coloured figure see Fouqué and Lévy, pl. XLV, fig. 1.

[2] Bayley, *Bull. Geol. Soc. Amer.* (1892) iii, 235–241, and in Diller, 201–209, pl. XXIX.

[3] Adams, *A. J. S.* (1894) xlviii, 10–16.

[4] Miller, *Rep. Bureau Mines* (1898) vii, 210–212 and (1899) viii, 204–225; Coleman, *ibid.* (1899) viii, 250–253.

[5] Card and Harper, *Rec. Geol. Sur. N. S. W.* (1905) viii, 34–36, pl. VIII, fig. 3.

[6] Dakyns and Teall, *Tr. Roy. Soc. Edin.* (1892) xxxvii, 163–172, with plate; Teall, *G. M.* 1900, 389. See also *20th Cent. Atlas*, 51, with plate.

apatite, and magnetite occur as accessories. Much of the orthoclase occurs in the form of rounded patches, $\frac{1}{4}$ to $\frac{3}{4}$ inch in diameter, which replace leucite crystals (fig. 15). A similar rock, differing by the presence of abundant nepheline, is found in the igneous complex of Magnet Cove, Ark.[1]

A *sodalite-syenite*, with little or no nepheline, seems to be an uncommon type. It has been found in the Highwood Mts

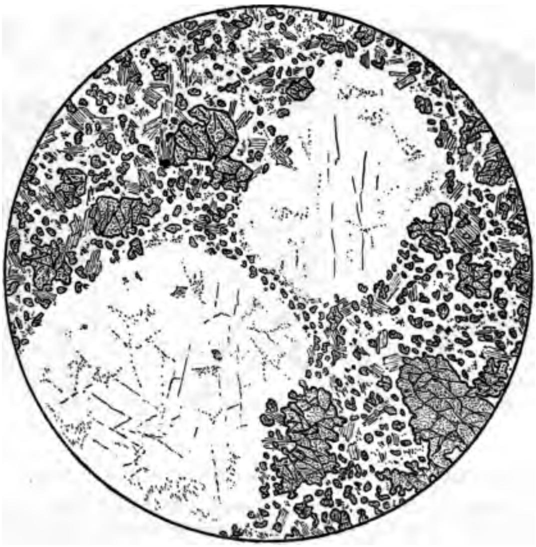

FIG. 15. MELANITE-LEUCITE-SYENITE (BOROLANITE), LOCH BOROLAN, SUTHERLAND; ×5.

Composed essentially of orthoclase and the iron-garnet (melanite) with some pale green biotite. The clear spaces represent pseudomorphs of orthoclase after leucite [2956].

[1] J. F. Williams, *Ign. Rocks Ark.* (1890) 267–276; Washington, *Bull. Geol. Soc. Amer.* (1900) xi, 399, and *Journ. Geol.* (1901) ix, 615–617. The latter author gives to this type the name 'arkite.'

of Montana[1] and at Cottonwood Creek[2] in the same State. A sodalite-syenite occurs, with nepheline-syenite, at Beloeil in the Montreal district. A very beautiful rock composed of sodalite and microperthite felspar forms veins in a nepheline-syenite in Ice River Valley, British Columbia[3]. It constitutes the most felspathic term in a series, the other extreme type being an ijolite[4].

In this place may be mentioned the *theralites*, which differ from the nepheline-syenites in having a plagioclase felspar,

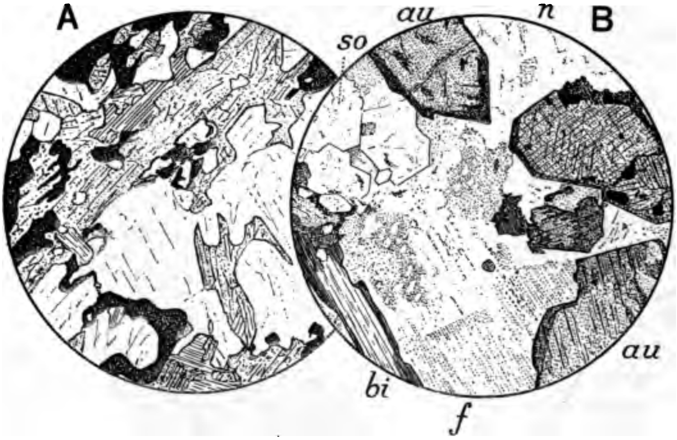

FIG. 16. NEPHELINE-BEARING ROCKS, U.S.A.; ×20.

A. Ijolite, Magnet Cove, Arkansas; composed of nepheline, augite, and deep brown melanite garnet (in irregular grains), with some pale biotite [3167].

B. Theralite, Gordon's Butte, Crazy Mts, Montana. In addition to felspar (*f*) and nepheline (*n*), there is a group of sodalite crystals (*so*). The ferro-magnesian minerals are pale augite (*au*), bordered with bright green ægirine, and some biotite (*bi*), pale in the interior but deep brown at the border [2795].

[1] Lindgren, *A. J. S.* (1893) xlv, 290–297; Weed and Pirsson, *Bull. Geol. Soc. Amer.* (1895) vi, 416, 417.

[2] Merrill, *Pr. U. S. Nat. Mus.* (1894) xvii, 671–673.

[3] Bonney, *G. M.* 1902, 199–206.

[4] Barlow, *Ottawa Natst.* 1902, 70–76.

though usually with orthoclase in addition. The original type is from the Crazy Mts, in Montana[1] (fig. 16, *B*). Here the idiomorphic augite, pale green to almost colourless in slices, is often surrounded by a narrow border of deep green ægirine. The felspar is partly a striated plagioclase, partly orthoclase or anorthoclase. A sodalite mineral occurs in addition to the nepheline, and the other constituents are biotite, apatite, and a little iron-ore.

In the *ijolite* type nepheline occurs to the complete exclusion of felspar, and is usually associated with augite, and often with melanite. A good example is found forming part of the remarkable igneous complex of Magnet Cove in Arkansas[2] (fig. 16, *A*). The nepheline-syenite of Dungannon (Ont.) passes into a hornblende-ijolite, consisting essentially of nepheline and green hornblende, with only a small amount of albite (Monmouth type)[3].

A more remarkable rock is Pirsson's *missourite*[4] from the Highwood Mts, Montana. It is quite devoid of felspar, consisting of olivine, augite, biotite, and leucite, with some apatite and iron-ore. The structure is thoroughly allotriomorphic. The rock is associated with, and passes into, a basic augite-syenite of the Shonkin type. It has a decided preponderance of the ferro-magnesian minerals; but the reverse is the case in another type ('fergusite') from the same district, which consists principally of leucite (replaced by orthoclase and nepheline) with augite[5].

Among special modifications of syenitic rocks may be mentioned the *syenite-aplites* and *syenite-pegmatites* described

[1] Wolff, *Notes on the Petrography of the Crazy Mts, etc., Northern Transcontinental Survey* (1885); and in Diller, 197–200. For coloured plate see Berwerth, *Lief.* II.

[2] Washington, *Bull. Geol. Soc. Amer.* (1900) xi, 400; *Journ. Geol.* (1901) ix, 618. This is the 'Ridge type' of Williams, *Ign. Rocks Ark.* (1890) 229–231.

[3] Adams, *A. J. S.* (1904) xvii, 269–276.

[4] *A. J. S.* (1896) ii, 317–323.

[5] Pirsson, *Bull.* 237 *U. S. Geol. Sur.* (1905) 83–89.

by Brögger as associated with the augite- and nepheline-syenites of Langesundsfjord. The pegmatites are remarkable not only for the frequent perthitic intergrowths of potash- and soda-felspars, but also for graphic intergrowths of the felspars with the ferro-magnesian minerals and with nepheline and sodalite; and they are famous as the home of many rare minerals. Some of these features are reproduced in the pegmatites associated with the Arkansas nepheline-syenites[1].

[1] J. F. Williams, *Ign. Rocks Ark.* (1890) 143–146, 238–258.

CHAPTER IV.

DIORITES.

THE diorites are plutonic rocks of medium to coarse texture, consisting essentially of a soda-lime felspar and hornblende with less important constituents. The family so defined cannot be regarded as a natural one, its members ranging in chemical composition from sub-acid to thoroughly basic. The gabbros (characterized by pyroxenes in place of hornblende) also include intermediate as well as basic rocks, and the distinction between the hornblende- and augite-bearing types is rather an artificial one. It was established before the strong tendency of augite to pass over into hornblende was thoroughly appreciated: later research has shown the certainty of some, and the possibility of many, of the rocks which have been termed diorites being really amphibolized pyroxenic rocks.

The more acid diorites contain free silica (*quartz-diorites*), and, except for the smaller proportion of quartz and the nature of the felspars, do not differ much from the hornblende-granites. They may have biotite in addition to hornblende (*quartz-mica-diorites*), or in some cases augite. In the *diorites* proper, without quartz, mica is not common, but the hornblende may be accompanied by augite or sometimes enstatite. The hornblende is more abundant relatively to the felspar than in the preceding types, and some of the more basic diorites consist chiefly of hornblende. These are the 'amphibolites' of some authors. In some types olivine enters as a constituent (*olivine-diorites*).

Constituent Minerals. The felspar of the diorites is *oligoclase, andesine,* or *labradorite,* or exceptionally a more basic variety. The twin-lamellation on the albite type is often accompanied by pericline- or carlsbad-twinning (fig. 3, *B*). In the quartz-diorites especially the crystals frequently show between crossed nicols a marked zonary banding, the central and marginal portions of a crystal often giving widely different extinction-angles, and the successive layers growing more acid from within outwards (fig. 3, *A*). In natural light the zones of growth may be indicated by the disposition of fluid-pores, minute scales of hæmatite, or other inclusions. The crystals are often clouded by a fine dust (possibly kaolin), and may also furnish by their alteration scales of colourless mica (paragonite ?), grains of epidote, calcite, *etc.* A little *orthoclase* may be present as an accessory, behaving in the quartz-diorites as in granites, while in typical diorites it occurs interstitially.

The *hornblende,* when idiomorphic, shows the prism-faces and usually the clinopinacoid, and terminal planes are often present. Twinning is common, and the prismatic cleavage is always well pronounced. In the quartz-diorites the mineral, usually in imperfect crystals, is green, as in granites; in more normal diorites it has brownish-green or greenish-brown colours; and in the most basic types the original hornblende is usually of some greenish shade of brown, or even approaches the deep brown of 'basaltic hornblende.' Pale colours result from bleaching, or are found in secondary outgrowths[1] of the brown crystals, and these are green rather than brown (fig. 18, *C*).

The deep brown *biotite* of the diorites occurs in idiomorphic flakes, or sometimes intergrown with hornblende. It is usually not rich in inclusions. It becomes green only by partial decomposition.

The rhombic pyroxene found in a few diorites is a variety poor in iron (*enstatite*) and is usually converted into pseudomorphous pale bastite.

When *augite* is present, it is of a variety sensibly colourless in slices. If idiomorphic, it shows the octagonal cross-

[1] Van Hise, *A. J. S.* (1887) xxxiii, 385–388, with figures.

section due to equal development of the pinacoids and prism-faces, with good prismatic cleavage and not infrequently lamellar twinning parallel to the orthopinacoid. A not uncommon feature in diorites is a parallel growth of augite and hornblende, a crystal-grain of the former mineral constituting a kernel, round which a shell of brown hornblende has grown, and this seems to occur specially in the neighbourhood of grains of iron-ore (fig. 18, *A*). This must be distinguished from another phenomenon frequent in the augite-bearing diorites, *viz.* the conversion of augite into brown hornblende as a secondary change. This process usually begins at the margin of a crystal or grain, but proceeds irregularly, showing a very intricate boundary between the two minerals and often ragged scraps of one enclosed by the other (fig. 17, *A*). When the conversion is complete, the secondary hornblende can be distinguished from original only by inference, as, *e.g.* when it shows the external form of augite. In both phenomena the augite and hornblende have their plane of symmetry and longitudinal axis in common, and in longitudinal sections both extinguish on the same side of the axis.

The *quartz* of quartz-diorites has the same general characters as that of granites.

The *olivine* which occurs in some basic diorites is often in rather rounded crystals enclosed by the hornblende. It is easily recognized by its high refractive index and very strong double refraction. The mineral is readily altered into serpentine, carbonates, and especially pale fibrous amphibole, the last often grown in crystalline continuity with adjacent original hornblende.

Among the iron-ores, *magnetite* is the most usual, but *ilmenite* is also found. Common accessories in some varieties are *zircon* and *sphene* in characteristic crystals. *Apatite* is general, and in some basic diorites abundant: in the coarse-grained rocks it sometimes builds rather large prisms.

Structure. The structure of the dioritic rocks is variable. In the quartz-diorites the mutual relations of the minerals are those noticed in granites, though sometimes a part of the felspar has crystallized before the ferro-magnesian

minerals. A micrographic intergrowth of quartz and felspar is not infrequent. Many of the quartzless diorites also follow what may be called the normal order of crystallization. Rosenbusch points out that the most marked pauses in the process of consolidation have occurred before the separation of the ferro-magnesian minerals and after that of the plagioclase; so that while the apatite, sphene, *etc.*, and the plagioclase may be markedly idiomorphic, the hornblende, biotite, and augite tend to occur in much more irregularly shaped crystals. When a miarolitic structure occurs, with a tendency to idiomorphism in the latest crystallized elements, it is commonly obscured by the cavities becoming filled by calcite and other secondary products.

A different type of structure, though connected by transitions with the preceding, is found in many dioritic rocks. Here the plagioclase has crystallized earlier, or at least ceased to crystallize earlier, than the bisilicates; so that the dominant felspar presents idiomorphic outlines to the hornblende and (if present) augite. These latter may wrap round, or even enclose, the felspar crystals, giving an 'ophitic' structure identical with that described below as characteristic of the dolerites. This is found more or less markedly in many of the more basic diorites, and is especially common in rocks in which the hornblende is in great part derivative after augite, though original hornblende moulded on felspar is also found.

Pegmatoid and aplitic structures are less common in this family than in the granites and syenites.

A porphyritic structure is not common in true diorites, but may come in as a marginal modification of a boss or stock, the porphyritic elements being crystals of hornblende or felspar.

As a more special type of structure may be mentioned the orbicular (in the so-called corsite or napoleonite), where the bulk of the rock consists of spheroidal growths. These have a radial structure, and consist of concentric shells composed essentially of hornblende and felspar alternately. A well-known rock of this character comes from San Lucia di Tallano

in Corsica[1]. Other orbicular diorites are recorded from California[2], and North Carolina[3].

Leading Types. The *quartz-diorite* of the Adamello Alps, on the border of Italy and the Tirol (Tonale type), comes very near in characters to some granites[4], and has also points in common with the monzonites. The dominant felspar is a striated plagioclase often showing zonary banding, and with a strong tendency to idiomorphic outlines; but there is frequently some orthoclase in addition, in irregular crystal plates moulded on or enclosing the triclinic felspar. Biotite is the most constant coloured element, but hornblende is also abundant. The mutual relations of the two are variable, and both may enclose the plagioclase. Interstitial quartz is abundant; patches of magnetite are often prominent; and zircon in little well-built prisms is of general occurrence.

Quartz-diorites more or less resembling the Tonale type are found among the plutonic complexes of Old Red Sandstone age ('newer granites') in Scotland. They show well the interstitial quartz, the zoned plagioclase crystals, and other characteristic features. A good quartz-mica-diorite comes from the lower part of Beinn Nevis. Other quartz-diorites occur about Garabal Hill, near the head of Loch Lomond[5], and show gradations on the one hand into granites, on the other into quartzless diorites (including mica-diorite and augite-diorite). Similar gradations are exhibited by the Beinn Cruachan rock[6] (fig. 17, *A*), which is in the main of the Tonale type. Of the three main masses of the 'Galloway granites' one, that of

[1] Cohen (3), pl. LXXI, fig. 3; Robertson, *Tr. G. S. Glasgow* (1883) vii, 210.

[2] Turner, *14th Ann. Rep. U. S. Geol. Sur.* (1894) Part II, pp. 475, 476 (Rattlesnake Bar).

[3] G. H. Williams, *Proc. Philad. Acad.* 1882, 59 (Yadkin River).

[4] This is the '*tonalite*' of vom Rath. Since it is an extreme type, and is classed by some petrologists with the granites, it is confusing to extend this name, as some writers have done, to all the quartz-diorites. Brögger restricts the term to the type free from any alkali-felspar; that with both an alkali- and a lime-soda-felspar he styles *adamellite*, and regards as the most acid member of his monzonite family.

[5] Dakyns and Teall, *Q. J. G. S.* (1892) xlviii, 104–120.

[6] Kynaston, *Ann. Rep. Geol. Sur.* for 1896, 24.

Criffel, has as its prevalent variety a quartz-diorite of the same type[1].

In Wicklow, to the east of Rathdrum, occur quartz-diorites and quartz-mica-diorites which in some particulars approximate to the granites, subordinate orthoclase accompanying the dominant triclinic felspar. The other minerals are pale green hornblende, ragged flakes of biotite, abundant quartz, apatite, and sometimes a little colourless augite[2].

In the United States, as in Britain, numerous rocks belonging here have been designated granite, or sometimes

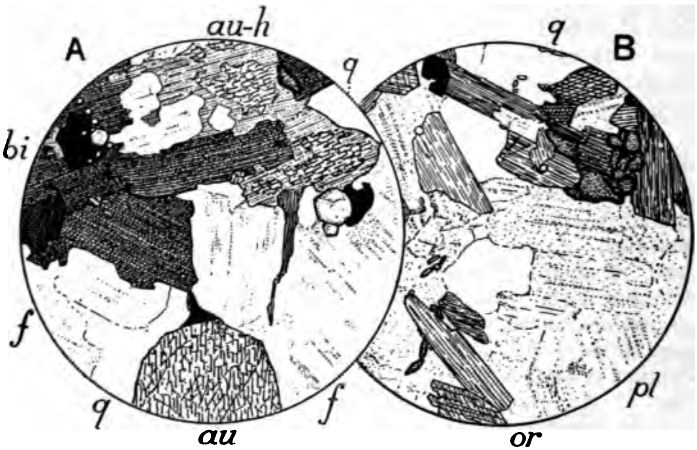

FIG. 17. QUARTZ-DIORITES; ×20.

A. Beinn Cruachan, Argyllshire. The felspar (*f*) is strongly zoned between crossed nicols, but approximates to the composition of oligoclase. The ferro-magnesian minerals are biotite (*bi*) and colourless augite (*au*), the latter partly transformed to light green hornblende (*au-h*). Magnetite, apatite, and sphene are also present, and quartz (*q*) is the latest product of crystallization [4876].

B. Near Grouse Lake, Sierra Nevada ('Granodiorite'): composed of green hornblende and plagioclase felspar (*pl*), with some biotite, orthoclase (*or*), quartz (*q*), sphene, magnetite, and apatite [3455].

[1] Teall, *Mem. Geol. Sur.*, *Silur. Rocks Scot.* (1899) 607–621.
[2] Hatch, *G. M.* 1889, 262, 263; see also Watts, *Guide*, 34.

granite-diorite. A type with subordinate potash-felspar, largely developed in the Sierra Nevada of California, has been styled 'granodiorite,' and is regarded by Lindgren[1] as intermediate between true quartz-diorite and quartz-monzonite (fig. 17, *B*). Of similar nature is the rock of Butte City, Mont., the chief constituents of which are acid labradorite, orthoclase, quartz, and green hornblende, with subordinate biotite[2].

As a typical quartz-diorite may be cited that described by Iddings[3] from Electric Peak in the Yellowstone Park. Here the dominant felspar ranges from oligoclase to labradorite, and there is sometimes orthoclase in addition; the quartz is in allotriomorphic grains; and the other constituents are biotite, hornblende, augite, hypersthene, and magnetite. Parallel intergrowths are frequent among the ferro-magnesian minerals, hypersthene being bordered by augite and the pyroxenes by biotite and hornblende[4]. A porphyritic quartz-mica-diorite was described by G. H. Williams[5] among the varied dioritic rocks of the Cortlandt district. The large felspar crystals are strongly zoned, but only occasionally lamellated.

A number of quartz-diorites, with biotite or hornblende or both, have been described by Howitt from Victoria (Swift's Creek[6], Noyang[7], Dargo[8]). Simple diorites without quartz are also found (Swift's Creek, *loc. cit.*). Quartz-mica-diorites from the Mt Macedon district of Victoria have been compared by Prof. Gregory[9] with the 'granodiorites' of the Sierra Nevada. Other examples occur in the Hauraki gold-bearing region of New Zealand[10], forming dykes of Palæozoic age.

[1] *A. J. S.* (1897) iii, 308–312; see also Turner, *17th Ann. Rep. U. S. G. S.* (1896) 636, 637, pl. XLII, A.
[2] Weed, *Journ. Geol.* (1899) vii, 740–744.
[3] *12th Ann. Rep. U. S. Geol. Sur.* (1892) 595–609; also in Diller, 243, 244.
[4] *Ibid.* pl. L.
[5] *A. J. S.* (1888) xxxv, 446.
[6] *Tr. R. S. Vict.* (1880) xvi, 11–88.
[7] *Ibid.* (1884) xx, 21–34.
[8] *Ibid.* (1887) xxiii, 139–142.
[9] *Ibid.* (1902) xiv, 191, 192.
[10] Sollas, *Rocks of Cape Colville Peninsula*, vol. I (1905) 126, 169, 170, with plates.

In South Africa quartz-hornblende-diorites have been described from the Gokwe and Vaal rivers[1].

A *mica-diorite*, without quartz, is not a common type. It is found as a local modification of biotite-granite between Carrick Mt and Arklow, in Wicklow. Dr Teall[2] describes a good example from Pen Voose in the Lizard district, Cornwall. This consists essentially of felspar and a reddish brown mica with only quite subordinate green hornblende and accessory sphene. From Allt a' Mhuillin, south of Lochinver, Sutherland, the same author notes a mica-diorite with interstitial felspar. Among the Cortlandt rocks, on the Hudson River, a pure mica-diorite occurs, beside various mica-hornblende-diorites. It is a rather coarse-grained aggregate of plagioclase (oligoclase-andesine) and very deeply coloured biotite, with accessory epidote, magnetite, abundant apatite, and sometimes a little quartz[3]. Mica-diorite has been noted near the Comstock Lode, Nevada.

Of simple *hornblende-diorite*, without quartz, good examples, of Palæozoic age, are found in Warwickshire and other parts of the Midlands. In the rock of Atherstone, Hartshill, the brown hornblende is in part idiomorphic towards the turbid felspar; but part of it, on the other hand, is derived from a colourless augite, and a kernel of the latter mineral sometimes remains unchanged. Grains of magnetite are present, and abundant prisms of apatite. Allport[4] noted also olivine, pseudomorphed by carbonates *etc.* Rather coarse-grained diorites are met with in the curious complex of igneous rocks in the Malvern district. A specimen taken near the New Reservoir consists essentially of idiomorphic greenish-brown hornblende and labradorite felspar. In the well-known diorite of Brazil Wood[5] in Charnwood Forest, Leicestershire, the

[1] Henderson, *Transvaal Norites, Gabbros, and Pyroxenites* (1898) 50, 51.

[2] Pl. xxxii, fig. 1; xlvii, fig. 3.

[3] G. H. Williams, *A. J. S.* (1888) xxxv, 443–445; Kemp, *ibid.* xxxvi, 247–254.

[4] *Q. J. G. S.* (1879) xxxv, 637–641. Some of the rocks included as diorites by this author would now be classed with the lamprophyres: see below, Chap. X; compare Watts, *Pr. Geol. Ass.* (1893) xv, 394–396.

[5] Hill and Bonney, *Q. J. G. S.* (1878) xxxiv, 224.

hornblende tends to embrace the felspar, and this departure from the granitic type of structure is observable in some other diorites from the Midland counties.

Various diorites occur in the interior of Anglesey. One between Gwindu and Llanfaelog is a coarse-textured rock consisting of greenish-brown hornblende and turbid felspar with magnetite and apatite. The minor intrusions near Llanerchymedd[1] are of a rather different type. Brown hornblende occurs in well-formed crystals and also in shapeless plates, which can sometimes be seen forming at the expense of a colourless augite. There is also green and colourless hornblende as secondary outgrowths from the primary crystals (fig. 18, *C*). Some of these rocks contain olivine, or rather its alteration-products, and but little felspar, affording a transition from diorite to hornblende-picrite[2]. Other olivine-bearing diorites occur near Clynog-fawr in Caernarvonshire[3]. Here the hornblende forms ophitic plates, and is probably in part derived from augite. The same remark applies to certain rocks at Penarfynydd[4] in the Lleyn peninsula, where both ophitic and idiomorphic augite may be seen partly converted into brown hornblende. Some thoroughly basic dioritic rocks, very like those of Anglesey, occur in the Lake District, *e.g.* at Little Knott[5], White Hause, and Great Cockup[6] in the Skiddaw district. The rock at the first-named locality shows beautifully the pale fringes of hornblende which form a new outgrowth from the original crystals. In the Isle of Man several small masses of diorite are found on Langness. The hornblende, of a greenish-brown tint, is perfectly idiomorphic, but often shows secondary outgrowths. The felspars are much decomposed. Abundant zoisite, epidote, calcite, *etc.*, have been produced, and the quartz which is always found is probably all secondary.

[1] *G. M.* 1887, 546–552. Other types of dioritic rocks from Central Anglesey were described by Blake, *Rep. Brit. Assoc.* for 1888, 403–406.

[2] Bonney, *Q. J. G. S.* (1881) xxxvii, 137–139; (1883) xxxix, 254–256; Adye's *Stud. Micropetr.* 17, 18, pl. IV, fig. 1.

[3] *Bala Volc. Ser. Caern.* 102–106.

[4] *Ibid.* 92–97.

[5] Bonney, *Q. J. G. S.* (1885) xli, 511–513, pl. XVI, fig. 2.

[6] Postlethwaite, *Q. J. G. S.* (1892) xlviii, 510.

Apatite is plentiful, but a little pyrites is usually the only iron-ore present.

The diorites of the Scottish Highlands are not yet described in any detail. Those of the Garabal Hill district include mica-diorite and augite-diorite. The pale green augite is usually in allotriomorphic grains irregularly bordered by green hornblende. Diorites, with other hornblendic rocks, occur near Inchnadamph in Sutherland[1]. Here the hornblende is in unusually perfect crystals (fig. 18, *B*), and a colourless augite sometimes accompanies it.

In America the Cortlandt rocks include diorites consisting of brown hornblende, andesine, apatite, and magnetite, sometimes with accessory hypersthene; and by failure of the felspar these rocks graduate into hornblende-rocks. There are also diorites with green hornblende[2]. From Alabama[3] are described both basic diorites and others of more acid nature, which contain a little quartz and orthoclase. The diorites described by Zirkel[4] from Nevada are chiefly of the more acid kind, sometimes carrying quartz or, again, passing into mica-diorite (Pah-Ute range). The diorites of the great laccolitic masses in Colorado, Utah, and Arizona, of which Cross[5] has given a full account, are also of relatively acid varieties, with quartz.

A number of dioritic rocks may be studied in the Channel Islands. A very fresh rock from the quarries of Delancy Hill, Guernsey, is an *augite-diorite*, with colourless augite as well as brown original hornblende. The latter mineral is moulded on the felspar-prisms, and often borders the augite with the usual crystallographic relation (fig. 18, *A*). In an augite-diorite from Ropewalk Quarry the colourless augite is partly in rounded grains enclosed by the felspar, partly in shapeless plates, and the brown hornblende, apparently an original mineral, is clearly of posterior consolidation to the felspar. Magnetite is plentiful, and there are some large crystals of a

1 Teall, *G. M.* 1886, 346–353.
2 G. H. Williams, *A. J. S.* (1888) xxxv, 441, 442.
3 Clements, *Bull. No.* 5 *Geol. Sur. Ala.* (1896) 152–165; **Brooks,** ***ibid.*** 189, 190.
4 *Micro. Petrogr. Fortieth Parallel* (1876), 85–93.
5 *Laccolitic Mountain Groups*, 14*th Ann. Rep. U. S. Geol. Sur.* (1895).

rhombic pyroxene replaced by bastite. An augite-diorite from Fort Touraille, in Alderney, gives evidence of the conversion of augite into hornblende. Some deep brown biotite is also present, and a little interstitial quartz. Among pyroxene-diorites from other areas may be mentioned one in the Cape Colville district of New Zealand, with augite and subordinate hypersthene[1].

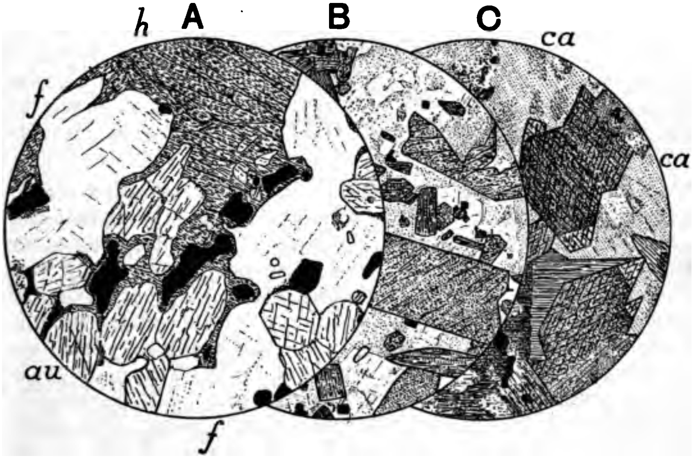

FIG. 18. BASIC DIORITES; ×20.

A. Augite-Diorite, Delancy Hill, Guernsey; with idiomorphic crystals of pale augite (*au*). The brown hornblende (*h*) is allotriomorphic, and is often interposed between augite and magnetite [431].

B. Diorite, near Inchnadamph, Sutherland; with idiomorphic hornblende [1685].

C. Secondary outgrowth from hornblende crystals in altered diorite, near Llanerchymedd, Anglesey. The felspar is largely replaced by calcite (*ca*), into which project the new growths of green hornblende. These are developed partly on the clinopinacoid faces of the primary brown crystals, partly on the terminal planes [539].

[1] Sollas, *Rocks of Cape Colville Peninsula* (1905) 236, 237, with plate.

CHAPTER V.

GABBROS AND NORITES.

THE gabbros and their allies are holocrystalline rocks, typically of plutonic habit, in which the essential constituents are a lime-soda-felspar and a pyroxene. Of intermediate to thoroughly basic character, they correspond partly with the diorites; but the more acid, and especially the quartz-bearing types, are less represented in the pyroxenic than in the hornblendic series. According to the dominant pyroxene, we recognise *gabbro*[1] proper (euphotide of Haüy) with diallage or augite, and *norite* (also called hypersthenite[2]) with a rhombic pyroxene. A few of the more acid rocks contain free silica (*quartz-gabbro* and *quartz-norite*). In most of the more basic varieties olivine becomes a characteristic mineral (*olivine-gabbro* and *olivine-norite*). The majority of the rocks in this family contain more or less olivine, but the mineral may be present or absent in different specimens of the same mass.

The gabbros and norites, indeed, show considerable variations in mineralogical constitution in parts of one mass, and some of the special types are probably to be regarded as merely local modifications. Thus, by the failure of one or other of the chief constituents of a gabbro we may have an almost pure *felspar-rock* (labrador-rock, anorthosite) or *pyroxene-rock*

[1] Gabbros in which the felspathic element is anorthite have sometimes been termed eucrites.

[2] In many of the 'hypersthenites' of the older writers the supposed hypersthene is only a highly schillerized diallage.

(diallage-rock *etc.*, 'pyroxenite' of Williams[1]). By the disappearance of pyroxene in an olivine-gabbro we have the so-called *troctolite* (Ger. Forellenstein), composed essentially of felspar and olivine: with abundant olivine and diminishing felspar we have transitions to the succeeding family of peridotites.

The name *hornblende-gabbro* has been used for rocks of this family which contain hornblende in addition to pyroxene, or in which original pyroxene is more or less completely changed to hornblende[2]. When the conversion is complete, we have no decisive criterion for verifying the derivative nature of the hornblende, and, as already remarked, the distinction between diorite and gabbro is a somewhat artificial one[3].

A historical account of the classification of the gabbros and allied rocks has been given by Bayley[4].

Constituent minerals. The felspar of the gabbros and norites ranges in different examples usually from *labradorite* to *anorthite*. It builds large irregularly-shaped plates with, as a rule, rather broad lamellæ[5] (albite twinning) often crossed by fine pericline-striation. The lamellæ not infrequently have something of a wedge-shape[6]. A crystal with broad albite lamellæ, if cut nearly parallel to the brachypinacoid, may appear untwinned. It is not safe to assume that the most constant twin-lamellation necessarily corresponds with the albite law: the felspar of some rocks of this family has pericline-twinning alone or predominant.

Zonary structure is typically not found. Besides fluid-pores and inclusions of earlier products of crystallization, the felspars often show more or less marked schiller-structure[7].

[1] *Amer. Geol.* (1890) vi, 40–49. Williams regarded the pyroxenites as a group coordinate with the peridotites. The name is ill-chosen, having been employed in two or three other quite different senses.

[2] R. D. Irving, *Copper-bearing Rocks of L. Superior*, 56–58, pl. VII.

[3] Prof. Cole restricts the name gabbro to the olivine-bearing (corresponding roughly with the basic) division, and styles the intermediate felspar-augite-rocks 'augite-diorite.'

[4] *Journ. Geol.* (1893) i, 435–456.

[5] Cohen (3), pl. xxv, fig. 3.

[6] *Ibid.* pl. xxvi, fig. 2.

[7] *Ibid.* pl. v, fig. 2.

The modes of alteration of the felspars are various: Rosenbusch notes the curious fact that calcite is seldom formed. The 'saussurite' change seems to belong often to dynamic metamorphism rather than to weathering (see below, Chap. XXI.). Any plagioclase more acid than labradorite is exceptional, and so is the occurrence of *orthoclase.*

The *augite* of the gabbros builds irregular crystal-plates and wedges of very pale green or light brown colour. Besides the usual prismatic cleavage, an orthopinacoidal cleavage and *diallage*-structure are very common (fig. 23, *A*), or instead of this there is sometimes a very minute striation parallel to the basal plane. Combined with the common orthopinacoidal twinning, this produces a characteristic 'herring-bone' appearance (fig. 19, *A*). The basal striation will be conveniently called the *salite* structure. Both this and the diallagic may

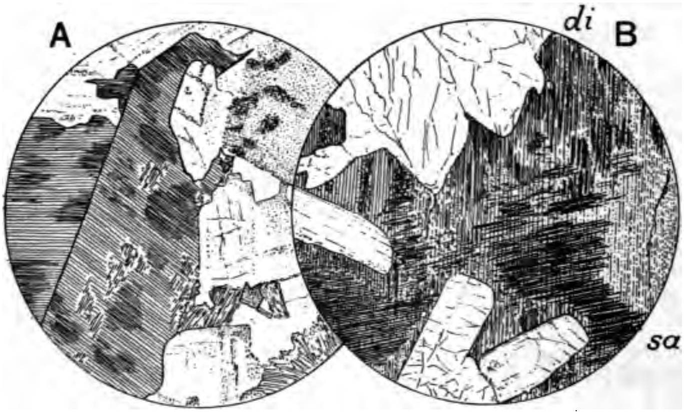

FIG. 19. GABBROS; ×20.

A. Quartz-Gabbro, Carrock Fell, Cumberland: composed of augite, labradorite, and a little altered biotite and clear quartz. The augite has the salite structure in conjunction with twinning on the orthopinacoid, giving the 'herring-bone' appearance [2950].

B. Gabbro, Glen an t-Suidhe, Arran: showing ophitic habit of augite. Almost the whole of this mineral in the field belongs to a single crystal, which has in places a strong 'schiller' striation, partly of the diallage type (*di*) and partly of the salite type (*sa*) [5041].

occur inconstantly, and both may be found in the same crystal (fig. 19, *B*). Decomposition of the augite gives rise characteristically to a scaly or fibrous aggregate of chlorite and serpentine with other products. Another common alteration is the conversion to hornblende[1], which may be light green and fibrous (uralite) or deep brown and compact.

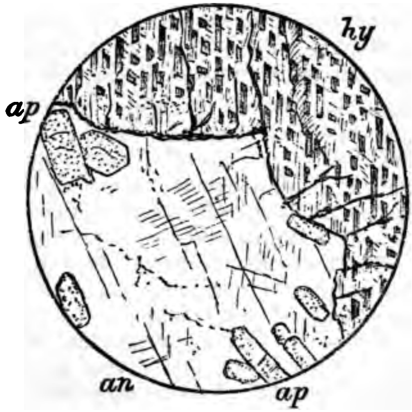

FIG. 20. NORITE (HYPERSTHENITE), COAST OF LABRADOR; ×20.

Consisting of hypersthene (*hy*), felspar (*an*), and apatite (*ap*). Schiller-inclusions are strongly developed in the hypersthene and to a less extent in the felspar [G 444].

The rhombic pyroxenes, *bronzite* and *hypersthene*, occur as accessory minerals in rather rounded but allotriomorphic crystals, while in the norites they often show but little crystal-outline. A schiller structure[2] is common in many norites and gabbros (fig. 20). The most usual alteration gives distinct pseudomorphs of the serpentinous mineral bastite. This is pale green or yellowish, with slight pleochroism and low polarization-tints. The pseudomorph is built of little fibres arranged longitudinally, and is traversed by irregular cracks

[1] See G. H. Williams, *A. J. S.* (1884) xxviii, 261–264; *Bull. No.* 28 *U. S. Geol. Sur.* (1886).

[2] Cohen (3), pl. v, fig. 3.

which the fibres do not cross (see fig. 28). The individual fibres give straight extinction, but, as there is a slight departure from perfect parallelism in their arrangement, a very characteristic appearance is offered. The rhombic pyroxenes also show uralitization.

In the rocks here included original *hornblende* is found only as an occasional accessory: a deep brown variety occurs in some norites. Brown *biotite* may also occur as a minor accessory (*e.g.* Carrock Fell; St David's Head), and it may be intergrown with augite (Stanner Rock, near New Radnor[1]).

When *olivine* is present, it builds imperfect crystals or rounded grains, colourless in slices. Where it adjoins felspar, it is often bordered by a rim of hypersthene. The olivine sometimes has schiller-inclusions. Its most characteristic mode of alteration is 'serpentinization.' This process begins round the margin of the crystal-grain and along the usually irregular network of cracks which traverses it. Along these, as a first stage, strings of granular magnetite separate out. The immediate walls of the cracks are converted into pale greenish or yellowish fibrous serpentine, the fibres set perpendicularly to the crack, and giving straight extinction and low polarization-tints. At this stage the meshes of the network are occupied by unaltered remnants of olivine. These may be subsequently altered to serpentine, which is of a different character from that first formed, being often sensibly isotropic[2]. As a last stage, some of the magnetite may be reabsorbed, giving a deeper colour to the serpentine pseudomorph. The change from olivine to serpentine involves an increase of volume, which gives rise to numerous radiating cracks traversing adjacent minerals. These cracks are injected with serpentine, usually isotropic (fig. 22).

Where primary *quartz* occurs in gabbros, *etc.*, it has the same properties as that in granites. Usually it forms part of a micrographic intergrowth.

Original iron-ores occur only sparingly in some rocks of

[1] Cole, *G. M.* 1886, p. 221, fig. 3.

[2] This effect is possibly due to the overlapping of a crowd of minute fibres or scales without any definite orientation. For successive stages of serpentinization of olivine see Cohen (3), pl. LIX.

the gabbro family, but sometimes become abundant. They are *ilmenite* (with leucoxene as a decomposition-product) and *magnetite*.

The *apatite* builds the usual hexagonal prisms or sometimes short rounded grains (fig. 20). In other accessories the rocks are usually very poor, zircon and original sphene being absent.

Structure. In texture the rocks of this family vary from medium to coarse grain. In some the individual crystals of felspar and pyroxene attain a large size, and they are then, as a rule, strongly affected by schiller-structures. Porphyritic structure is very rarely met with in the gabbros and norites.

Apatite, iron-ores, and olivine, when present, are the earliest minerals, and are clearly idiomorphic, while in the special types containing orthoclase and quartz these minerals have always crystallized last. But as regards the two main constituents, augite and plagioclase, the mutual relations are not always the same. In many gabbros the felspar is more or less distinctly embraced by the augite or diallage, but if this character becomes marked there are often other features which indicate a transition to the dolerite type. The more typical gabbros are often thoroughly hypidiomorphic; or the augitic constituent, especially if very abundant, may be embraced by the felspar. When a rhombic pyroxene enters, it is idiomorphic towards the monoclinic, and usually towards the felspar also.

In many plutonic rocks there is an evident tendency for the earlier formed minerals to serve as nuclei round which the later ones have crystallized. This tendency is most marked in basic and ultrabasic rocks. Thus in gabbros and norites the pyroxenes often form a more or less continuous ring or '*corona*' round olivine or iron-ores (fig. 21). This is the 'celyphitic structure' of Rosenbusch. Bayley[1], while noting this feature, further describes fibrous intergrowths of felspar and augite surrounding olivine or magnetite. These seem to be original, but in other cases there is reason to believe that a mineral bordering another one is of secondary origin.

[1] *Amer. Journ. Sci.* (1892) xliii, 515–518; *Journ. of Geol.* (1893) i, 702–710.

Good examples are figured and described by G. H. Williams[1] in the hypersthene-gabbros of the Baltimore district. Here both hypersthene and diallage are surrounded by a double '*reaction-rim*' of hornblende, interposed between the pyroxene and the felspar and due to a reaction between them. The inner zone of the rim is of fibrous, the outer of compact hornblende.

Leading types. We begin with the rather exceptional rocks in which free silica has been developed as an original constituent. A good example of a *quartz-gabbro* is that of Carrock Fell, in Cumberland[2] (fig. 19, *A*). The essential constituents are a somewhat basic variety of labradorite and an augite with basal striation. Imperfect prisms of enstatite also occur, and there is often a parallel intergrowth of the two pyroxenes. The augite is often converted into a greenish fibrous hornblende and the enstatite into bastite. Biotite is found locally. Magnetite and ilmenite occur, sometimes in evident intergrowths. Quartz is found partly in interstitial grains but chiefly in micrographic intergrowth with felspar, some of which is orthoclase. The rock varies much, the central part of the mass being rich in quartz, while the margin is highly basic, free from quartz and remarkably rich in iron-ores and apatite. The mutual relations of the felspar and augite vary, but on the whole the augite tends to envelope the felspar.

The coarse intrusive masses in the district of St David's Head, Pembrokeshire, as described by Mr Elsden[3], contain both enstatite and augite, and vary between quartz-norite and quartz-gabbro. Biotite is sometimes present (Carn Llidi), and orthoclase may become a noticeable constituent (Carn Trelwyd). The plagioclase felspar is in general not of a basic variety.

Quartz-gabbros more or less comparable with the Carrock

[1] *Bull. No.* 28, *U. S. Geol. Sur.* (1886), with plates.

[2] *Q. J. G. S.* (1894) l, 316–318, pl. XVII: (1895) li, 125. The rock has been termed hypersthenite, but the rhombic pyroxene is always subordinate to the monoclinic and sometimes wanting. See also *20th Cent. Atlas*, 1–3, with plate.

[3] *Q. J. G. S.* (1905) lxi, 584–592, pl. XXXIX.

Fell rock have been described from Minnesota[1], Southern India[2], and elsewhere.

The well-known rocks of the Lizard district[3] in Cornwall are, for the most part, simple *gabbros* without olivine, although that mineral occurs in some varieties. Judging from the cases in which precise determinations have been made, the felspar seems to be labradorite in the less basic rocks, anorthite in the most basic. It shows broad albite-lamellæ, often crossed by others following the pericline law. The pyroxene varies from a pale green diopside, almost colourless in slices, to typical diallage, the diallagic structure being often seen to affect only part of a crystal. The enstatite-group is wanting or rare. When olivine occurs, it builds colourless grains, showing various stages of serpentinization.

The Lizard gabbros exhibit, however, numerous modifications which are ascribed to dynamic metamorphism, especially the conversion of the felspar to 'saussurite' and of the augite to amphibole. The minutely granular mineral-aggregate known as saussurite is opaque in any but the thinnest slices, and can be studied only under high magnifying powers. The change may be seen to begin in spots in the felspar crystals and spread to the whole. The pyroxene passes over into uralitic or actinolitic or compact hornblende in different cases[4], the secondary amphibole being pale green or brown or colourless, or sometimes having a bright emerald-green colour (smaragdite). According as one or both of these changes have affected the original felspar-pyroxene-rock, we have saussurite-diallage-gabbro, felspar-hornblende-gabbro, or saussurite-hornblende-gabbro. At Karakclews occurs a rock consisting of a fine-grained aggregate of augite (malacolite), labradorite, sphene, and an unknown substance, brown by transmitted and white by reflected light. Dr Teall[5] states that much of the so-called saussurite of the Lizard is similar to this rock in composition. Another mineral considered to be of secondary origin is the

[1] Winchell, *Amer. Geol.* (1900) xxvi, 348–353, pl. XII, fig. 2.

[2] Holland, *Q. J. G. S.* (1897) liii, 405–417.

[3] Teall, *G. M.* 1886, 483–485. For description of particular varieties see Bonney, *Q. J. G. S.* (1877) xxxiii, 884–915, and other papers.

[4] Teall, pl. XVIII, fig. 2.

[5] *M. M.* (1888) viii, 118.

rhombic amphibole anthophyllite[1]. This sometimes occurs in colourless and rather fibrous crystals, forming a zone round grains of altered olivine, and surrounded in turn by an outer zone of green actinolite.

Gabbros from Guernsey (Bellegrève) exhibit very beautifully the conversion of colourless augite into brown or greenish-brown compact hornblende, the process being seen in every stage. In some slides no augite remains, and, without comparison with other specimens, the rock might be taken for a true diorite, but the hornblende is probably all derivative. The ferro-magnesian silicates are often moulded on the felspar, which is of a basic variety. Magnetite and apatite are the only other constituents. The gradual transformation of augite to hornblende is well displayed also in some gabbros from the Girvan district of Ayrshire (Pinbain Burn *etc.*).

Gabbros without olivine are met with in Canada, New Hampshire, and other parts of America. Some from the north-western part of the Adirondacks, N.Y.[2], consist essentially of felspar, in general labradorite, and augite, often transformed to compact hornblende. Usually the ferro-magnesian mineral predominates, but there are rapid transitions to a highly felspathic type. Other gabbros in the same district have accessory hypersthene. Gabbros without, as well as others with, olivine are largely developed in the Lake Superior region and the neighbouring parts of Minnesota, Wisconsin, *etc.*[3] An interesting type is the *orthoclase-gabbro* of Irving, in which the plagioclase felspar is oligoclase or an allied variety, and some orthoclase occurs in addition. The augite may be diallagic and is often uralitized; apatite is abundant; and the iron-ore is a highly titaniferous magnetite (Duluth and Lester River, Minn., *etc.*). These rocks recall in some respects the essexite type.

The basic plutonic rocks of Tertiary age in Skye[4], Mull[5],

[1] Teall, *M. M.* (1888) viii, 119.
[2] Smyth, *Bull. Geol. Soc. Amer.* (1895) vi, 263–284.
[3] Wadsworth, *Prelim. Descr. of the Perid., Gabbros, etc., of Minn.* (1887); R. D. Irving, *Copper-bearing Rocks of L. Superior, Monog. No.* 5 *U. S. Geol. Sur.* (1884).
[4] *Mem. Geol. Sur., Tert. Ign. Rocks Skye* (1904), Ch. viii.
[5] Judd, *Q. J. G. S.* (1886) xlii, 49–89, pl. IV.

Arran (fig. 19, *B*), Ardnamurchan, and St Kilda are mostly *olivine-gabbros*. The olivine is in many cases of a variety rich in iron and gives rise to much magnetite-dust as an alteration-product. Original iron-ores and apatite may or may not be present. The felspar is usually a labradorite, and this, rather than the pyroxene, tends to assume crystal outlines, the structure of the rock being often subophitic. The augite, as a rule, has a striation parallel either to the basal plane or to the orthopinacoid, with more or less marked schillerization. A rhombic pyroxene is only an exceptional accessory constituent.

Among American olivine-gabbros[1] those described by Irving[2] from the Lake Superior region tend to the ophitic type of structure. The felspar is usually anorthite or some other basic variety; the augite sometimes, but not always, shows the diallagic character; the iron-ore, often in large grains, is magnetite only slightly titaniferous; and apatite is rare. A rock from Pigeon Point, Minn.[3], consists of fresh labradorite, purplish pink titaniferous augite, olivine, titaniferous magnetite, and a little apatite. One modification contains large porphyritic crystals of the felspar. The large gabbro mass at the base of the Keweenaw formation in north-eastern Minnesota[4] consists essentially of a basic labradorite, augite, an olivine rich in iron (hyalosiderite), and a non-titaniferous magnetite; but wide differences in the relative proportions of these constituents give rise to numerous varietal forms.

In the *essexites*, sometimes regarded as a distinct family, the dominant labradorite felspar is accompanied by a variable amount of orthoclase, and sometimes by a little nepheline or sodalite. Olivine is usually present, and the other ferro-magnesian minerals may include augite, hornblende, and biotite in various relative proportions. The original rock, described by Sears[5], came from the nepheline-syenite district

[1] For coloured plate of example from New Hampshire see Berwerth, *Lief.* II.

[2] *Copper-bearing Rocks of L. Superior* (1884), with coloured plates.

[3] Bayley, *Bull. No.* 109 *U. S. Geol. Sur.* (1893) 32–38, pl. v.

[4] Bayley, *Journ. of Geol.* (1893) i, 696–714.

[5] *Bull. Essex Inst.* (1891) xxiii; see also Washington, *Journ. Geol.* (1899) vii, 52–64.

of Salem, in Essex County, Mass. Here the pale green augite is bordered by brownish hornblende, and brown biotite is intimately associated with them. The rounded grains of olivine are often pseudomorphed by biotite-aggregates, green hornblende, and granular augite. The iron-ore is titaniferous, and gives rise to secondary sphene. Apatite is abundant in irregular grains as well as in slender prisms. The felspar, in idiomorphic crystals, is chiefly an acid labradorite, but a subordinate amount of alkali-felspar is also present, and perhaps some nepheline. A similar rock is found at Mount Royal and other places near Montreal[1]. Here the augite is of a reddish-violet colour, probably titaniferous. The rock passes into a theralite carrying both nepheline and sodalite. An essexite has been described from the Rosita Hills, Colorado[2]. Brögger's rock from Gran, in the Christiania basin, is similar. Here hornblende is wanting, the dominant coloured silicate being a violet titaniferous augite[3]. This Norwegian area, however, affords a considerable variety of essexites from several localities.

In Scotland *norites* occur in Aberdeenshire, Banffshire, and other districts. One from Towie Wood, near Ellon, consists essentially of labradorite and a rhombic pyroxene, which is pale and without schiller-structure (fig. 21, *B*); while others from the same neighbourhood contain in addition augite, hornblende, and biotite[4]. Examples from near Lochinver, Sutherland, contain brown hornblende, and the felspar is not always of a very basic variety (fig. 21, *A*). The Tertiary plutonic rocks of Britain include few norites, though beautiful examples, with and without accessory augite, are found near Glenloig, Glen an t-Suidhe, Arran[5].

A well-known American norite comes from the coast of Labrador (fig. 20). The hypersthene has a strong schiller-structure, and sometimes encloses small intergrown patches of

[1] Dresser, *Amer. Geol.* (1901) xxviii, 205, 206 (Shefford Mt).

[2] Cross, *Proc. Colo. Sci. Soc.* (1887) 246, 247.

[3] *Q. J. G. S.* (1894) l, 18.

[4] For an olivine-hyperite from the same neighbourhood see *20th Cent. Atlas*, 30, with plate. A norite from Banff contains deep brown hypersthene with schiller-structure.

[5] *Mem. Geol. Sur. Scot., Geol. N. Arran* (1903) 108.

brown hornblende and biotite. The other main constituent is felspar (usually typical labradorite but sometimes a more basic variety), moulded on the imperfect crystals of hypersthene. Stout prisms of apatite also occur, and sometimes patches of iron-ore bordered by brown mica. Norites are found also in the Sudbury district of Canada.

A considerable development of norites and hypersthene-bearing gabbros is found in the Atlantic states from Virginia to New York. G. H. Williams[1] described the hypersthene-gabbro of the Baltimore neighbourhood and its conversion to 'gabbro-diorite' by uralitization of the pyroxenes. A quartz-norite is represented in the same district (Mt Hope)[2]. In

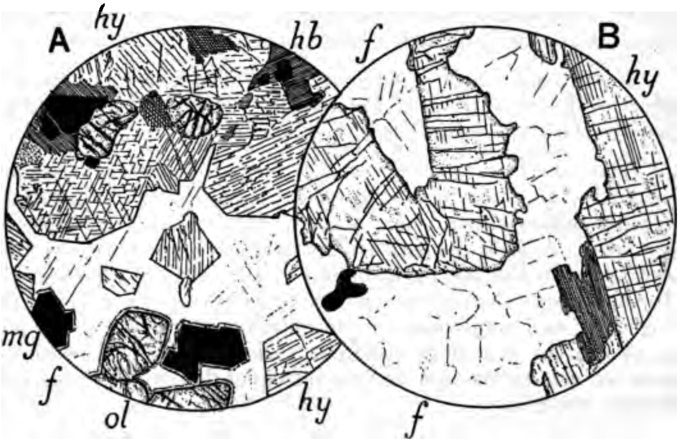

FIG. 21. NORITES, SCOTLAND; × 20.

A. Badenaban, near Lochinver, Sutherland. The constituents are magnetite (*mg*), olivine (*ol*), hypersthene (*hy*) often with intergrowths of augite, deep brown hornblende (*hb*), and clear felspar (andesine). The magnetite and olivine, where they adjoin felspar, are bordered by a narrow fringe of green pyroxene [1658].

B. Towie Wood, Ellon, Aberdeenshire. Composed essentially of hypersthene and felspar (labradorite), with accessory magnetite and biotite, or in other parts of the slice brown hornblende [2713].

[1] *Bull. No.* 28, *U. S. Geol. Sur.* (1886), with plates.
[2] Grant, *John Hopk. Univ. Circ.* (1893), xii, 48.

Cecil County, Md., according to Miss Bascom[1], the prevalent type is a norite; but gabbro and hypersthene-gabbro are also found, including some quartz-bearing varieties. The conversion of both pyroxenic minerals to hornblende is a wide-spread effect[2]. From the Adirondacks Kemp[3] describes rocks composed essentially of augite, hornblende, hypersthene, and felspar. Norites and allied types are included among the Cortlandt rocks on the Hudson River[4]. The norite proper consists mainly of andesine and hypersthene, both with schiller-inclusions. There is accessory biotite, and a remarkable feature is the occurrence of large crystals of orthoclase enclosing the other minerals in 'pœcilitic' fashion. In other rock-types from this district the hypersthene is associated with green or brown hornblende (hornblende-norite), with biotite and magnetite (mica-norite), or with augite and biotite (augite-norite).

Norites are found in some variety in the Zwartkoppies and Marico districts of the Transvaal[5]. They include quartz-norites with interstitial micropegmatite.

The *eucrite* type, in which the felspathic element is consistently of a very basic species (anorthite or bytownite), usually differs also in some other particulars from the normal gabbros. Among the British Tertiary rocks eucrites are well developed in the Isle of Rum and in the Carlingford district[6]. In these rocks rhombic and monoclinic pyroxenes usually occur together, and sometimes are intimately intergrown. Olivine is present or absent in different varieties. This mineral, as well as the pyroxenes, is not infrequently moulded on the felspar crystals.

The *felspar-rocks* known in America as anorthosites must be regarded as peculiar members of the gabbro family. Such

[1] *Geol. Cryst. Rocks Cecil Co., Maryland Geol. Sur.* (1902) 121–131.

[2] See also Miss Bascom, *Bull. Geol. Soc. Amer.* (1905) xvi, 311–313, pl. LVII (Piedmont district, Penna.); Chester, *Bull.* 59 *U. S. Geol. Sur.* 1890 (Delaware).

[3] *19th Ann. Rep. U. S. Geol. Sur.* (1899), part III, pl. LX, *A*.

[4] G. H. Williams, *A. J. S.* (1887) xxxiii, 135–144, 191–194.

[5] Henderson, *Transvaal Norites, Gabbros and Pyroxenites* (1898).

[6] Von Lasaulx, *Sci. Proc. Roy. Dubl. Soc.* (1878) ii, 31–33; Sollas, *Tr. Roy. Ir. Acad.* (1894) xxx, 482–487.

rocks, of pre-Cambrian age, occupy extensive tracts in Minnesota[1] *etc.*, near Lake Superior. The felspar which makes up almost the whole of these coarse-textured aggregates varies from labradorite to anorthite in different localities[2]. A little augite, of faint violet-brown tint in sections, is the only other original mineral, and this occurs both in grains and as minute parallel interpositions in the felspar. Similar rocks have been described by Adams[3] in the so-called Norian of several districts in Canada, by Kemp[4] in the Adirondacks, *etc.* In our country gabbros pass only locally into labradorite-rocks by the failure of the pyroxenic constituent (Lenkeilden Cove at the Lizard, Athenree in Tyrone[5]).

Contrasted with these are the pure *pyroxene-rocks*, to which G. H. Williams has given the name 'pyroxenite.' The Webster type[6], as described from North Carolina and Maryland, consists of a rhombic and a monoclinic pyroxene forming an even-grained crystalline aggregate. It is in fact a bronzite-diopside-rock. Another example, from Montana[7], consists of light green diallage and colourless enstatite with some brown mica and only occasional felspar. From the same district comes a hypersthene-hornblende-rock, sometimes rich in green pleonaste; while rocks composed essentially of augite and hornblende have been recorded from Alabama[8] and from Mariposa Co., Cal.[9] A pyroxene-rock from the John Day Basin, Oregon[10], consists of lamellar intergrowths of diallage

[1] R. D. Irving, *Copper-bearing Rocks of L. Superior*, 59–61, pl. VII, fig. 4; Lawson, *Bull. No.* 8 *Geol. and Nat. Hist. Sur. Minn.* (1893) and *abstr.* in *M. M.* x, 263. The very coarse-textured felspar-rock of Labrador, with its beautiful schiller-structure, is in all mineralogical collections.

[2] The mineralogical term 'anorthose' (Delesse), from which anorthosite is named, is synonymous, not with anorthite, but with plagioclase generally.

[3] *Can. Rec. Sci.* vi, 190 (Quebec Province); see also Coleman, *Journ. Geol.* (1896) iv, 907–911 (Rainy Lake region).

[4] *Bull. Geol. Soc. Amer.* (1894) v, 215, 216; *Geology of Moriah and Westport, Bull. N.Y. State Mus.* (1895) iii, 337.

[5] Watts, *Guide*, 73.

[6] G. H. Williams, *Amer. Geol.* (1890) vi, 40–49, pl. II, fig. 2.

[7] Merrill, *Proc. U. S. Nat. Mus.* (1894) xvii, 662, 657, 658.

[8] Clements, *Bull. No.* 5 *Geol. Sur. Ala.* (1896) 163, 164.

[9] Turner, *A. J. S.* (1898) v. 423, 424.

[10] Calkins, *Bull. Dep. Geol. Univ. Cal.* (1902) iii, 118–120.

and enstatite. Among other types consisting wholly of ferro-magnesian silicates we may mention a hypersthene-biotite-rock from Hamilton River in Labrador[1] and an enstatite-rock from the Transvaal[2]. The Webster type has been recorded from the Heazlewood district of Tasmania[3]. In the British Isles gabbros pass only locally into augite- or diallage-rock, as at Lendalfoot, Ayrshire[4] (fig. 23, *A*); while rocks consisting essentially of pyroxene are also found locally in other associations. One occurs at Ledmore as part of the complex of syenitic rocks of Western Sutherland. It is composed of augite and melanite, with some biotite and magnetite and rather conspicuous crystals of apatite.

By the dwindling and disappearance of the pyroxene, olivine-gabbro passes into *felspar-olivine-rock*, known as

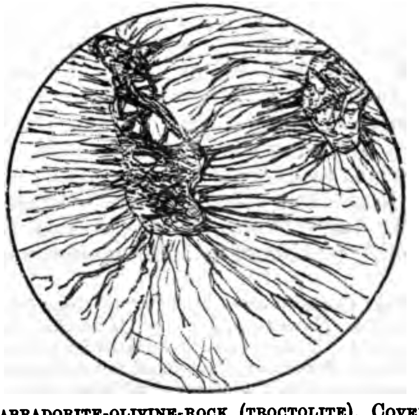

FIG. 22. LABRADORITE-OLIVINE-ROCK (TROCTOLITE), COVERACK COVE, CORNWALL; × 20.

The olivine is almost wholly converted into serpentine (a few clear granules remaining), and the consequent expansion has caused radiating fissures through the surrounding felspar [1116].

[1] Ferrier, *Ann. Rep. Geol. Sur. Can.* (1896) viii, 344 L.

[2] Maskelyne, *Phil. Mag.* (1879) vii, 135, 136; Hatch, *Tr. Geol. Soc. S. Afr.* (1904) vii, 4 (Marico).

[3] Twelvetrees and Petterd, *Proc. Roy. Soc. Tas.* for 1897, 29–32, 36, 37.

[4] Bonney, *Q. J. G. S.* (1878) xxxiv, 778–780.

troctolite (Ger. Forellenstein). This consists essentially of a lime-soda-felspar, typically labradorite, with olivine, which may be more or less serpentinized. Such rocks are known in the gabbro area of the Lizard[1] (fig. 22), and in Minnesota[2] and other American districts of basic plutonic intrusions.

It has been noticed above that an ordinary gabbro may pass into a variety very rich in magnetite and ilmenite (*e.g.* Carrock Fell). Some gabbros and norites, in Scandinavia, in Minnesota[3], in the Adirondacks[4], *etc.*, show very basic modifica-

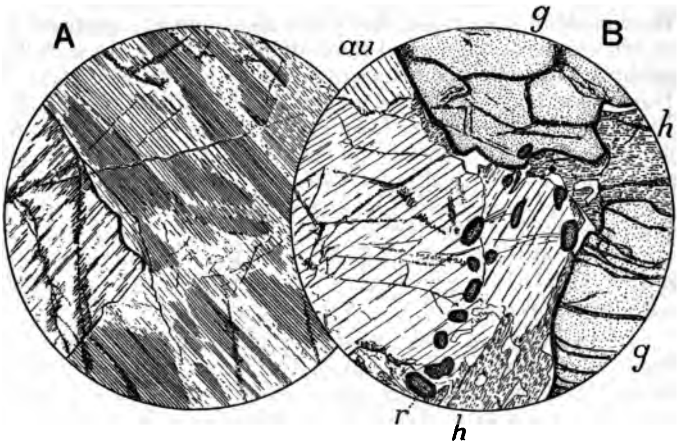

FIG. 23. PYROXENIC ROCKS, SCOTLAND; × 20.

A. Diallage-rock, Lendalfoot, Ayrshire: showing 'schiller' striation parallel to the orthopinacoid. In the crystal to the left there is only an incipient development of this structure [4093].

B. Eclogite, near Glenelg, Invernessshire: composed of garnet (*g*), pale augite (*au*), and green hornblende (*h*), with grains of deep brown rutile (*r*) and small interstitial patches of quartz [3597].

[1] Teall, pl. VIII, fig. 2.

[2] Wadsworth, *Prelim. Descr. Perid. Gabb. etc. Minn.* (1887) 95, pl. V; Winchell, *Amer. Geol.* (1900) xxvi, 281–284.

[3] Wadsworth, *ibid.* 63, 64, pl. VI, fig. 1; Irving, *Copper-bearing Rocks of L. Superior*, 51, 52; Winchell, 10*th Ann. Rep. Minn. Geol. Sur.* (1882), 80–83.

[4] Kemp, *Bull. Geol. Soc. Amer.* (1894) v, 222.

tions, which are almost pure *iron-ore-rocks*[1]. As a rule, they are highly titaniferous. An augite-magnetite-rock, consisting of crystal-grains of augite set in a framework of titaniferous magnetite, is one of the varieties of the curious banded gabbros of Skye[2].

Among rocks of somewhat doubtful affinities must be mentioned the small group of the *eclogites*. The typical eclogite of Haüy consists essentially of an aluminous augite (omphacite) and red garnet, with sometimes quartz, hornblende, actinolite (smaragdite), cyanite, or other accessories. From their mode of occurrence, the rocks are commonly regarded as of true igneous origin, and their affinities are clearly with the gabbros. British examples are found in the district of Loch Duich[3] and Glenelg, on the west coast of Scotland (fig. 23, *B*). From Beinn Fyn, near Loch Maree, comes a *hornblende-eclogite*[4], consisting mainly of garnet and green hornblende with some quartz, plagioclase, *etc.* A handsome rock having the same general characters occurs near Loch Laxford, in Sutherland[5] (fig. 88, below). Another rock comparable in many respects with eclogite is recorded from Mountain Lodge, near Pettigo, Donegal[6]. All these examples are associated with Archæan gneisses.

In California a rock consisting of garnet and greenish brown hornblende, with grains of rutile, has been noted from Santa Catalina Is.[7]; and other eclogites and hornblende-eclogites, some with glaucophane, have been described from various localities in the same State[8].

[1] Vogt, *G. M.* 1892, 82–86 (*abstract*). For descriptions of iron-ore-rocks from Cumberland in Rhode Is. and Taberg in Sweden, see Wadsworth, *Bull. Mus. Comp. Zool. Harv.* (1881) vii, 185-187; *Lith. Stud.* 75–81, pls. I, II.

[2] Geikie and Teall, *Q. J. G. S.* (1894) l, pl. XXVIII.

[3] Teall, *M. M.* (1891) ix, 217, 218. See also Flett, *Summary of Progress Geol. Sur.* for 1905, 160–166 (An. Cruachan).

[4] Bonney, *Q. J. G. S.* (1880) xxxvi, 105, 106.

[5] *G. M.* 1891, 171, 172.

[6] Cole, *Tr. Roy. Ir. Acad.* (1900) xxxi, 457, 458, pl. XXVI, fig. 6.

[7] W. S. T. Smith, *Pr. Cal. Acad. Sci.* (1897) i, 62–64.

[8] Holway, *Journ. Geol.* (1904) xii, 347–358.

CHAPTER VI.

PERIDOTITES (INCLUDING SERPENTINE-ROCKS).

THE peridotites are holocrystalline rocks of ultrabasic composition, in which felspar is typically absent, and olivine is the most prominent constituent. They were separated from the more normal basic rocks by Rosenbusch; but, though their marked characters make it desirable to discuss them apart, they do not constitute a family comparable, *e.g.*, with that of the gabbros in importance. The peridotites do not usually occur as large bodies of uniform rock. In many localities they are seen to be only local modifications of olivine-gabbros, olivine-norites, or olivine-diorites, and they show frequent transitions from one type to another.

For so small a group a needless multiplicity of names has been created. The simple olivine-rock is the 'dunite' of Hochstetter. With the addition of enstatite we have the 'saxonite' of Wadsworth[1], 'harzburgite' of Rosenbusch; other types are styled 'lherzolite,' 'eulysite,' *etc.*; and the name 'picrite' is used for those characterized by augite or hornblende, usually with some felspar. For our purposes it will be sufficient to separate the *picrites*, rich in the bisilicate constituents and having usually subordinate plagioclase, from the more typical *peridotites*, very rich in olivine and non-felspathic. Different types may be specified by prefixes in the customary way (*e.g.* hornblende-picrite, enstatite-peridotite, *etc.*). In addition there are ultrabasic rocks rich in lime-felspar.

[1] *Lithological Studies* (1884, Camb., Mass.). This work contains many descriptions of peridotites and meteorites, with a number of useful coloured plates.

Many of the meteorites ('stony meteorites' as distinguished from meteoric irons) have a mineral composition allied to that of the terrestrial peridotites, but often with special accessory minerals and peculiar structures[1].

In consequence of the unstable nature of their principal constituent mineral, the peridotites are very readily decomposed, and most of the serpentine-rocks have originated in this way.

Constituent minerals. In the typical peridotites *olivine* makes up from half to nearly the whole of the rock. If not so abundant that its crystals interfere with one another, it is usually idiomorphic. The mineral is colourless in thin slices, and shows either irregular cleavage-traces or a network of fissures. It often has schiller-inclusions of the nature of minute negative crystals enclosing dendritic growths of magnetite (fig. 27, *A*). Alteration along cracks gives rise to strings of magnetite granules, and complete destruction produces pseudomorphs of greenish or yellow serpentine, or sometimes colourless fibrous tremolite, *etc.*

Of the other ferro-magnesian silicates the commonest in typical peridotites is a rhombic pyroxene; either colourless or pale yellow (*enstatite*) or with faint green and rose pleochroism (*bronzite*): varieties rich in iron do not often occur. The crystals often tend to be idiomorphic. Marked schiller-structures are not very common. Decomposition produces pseudomorphs of bastite[2]. The *augite* is either light brown to colourless, with a high extinction-angle (about 40°) as in many dolerites *etc.*, or it may show a faint green tint (chrome-diopside). A conversion to brown hornblende is common in the picrites, and so also are parallel growths of augite and brown hornblende, the former being the kernel[3].

The *hornblende* may be a green or pale actinolitic variety, but in many of the picrites it is 'basaltic' hornblende with an extinction-angle of about 20° and colour varying from deep brown to colourless. The pale variety seems due to bleaching,

[1] See Farrington, *Journ. Geol.* (1901) ix, 51–66, 174–190, 393–408, 522–532.

[2] Fouqué and Lévy, pls. LIII, LIV.

[3] Cohen (3), pl. XXXII, fig. 1.

often accompanied by a discharge of magnetic dust. The *biotite* of peridotites is also frequently of a pale tint.

Some peridotites have little octahedra of *magnetite*, but some other spinellid mineral is more characteristic. It may be *chromite* (deep brown or opaque), *picotite* (coffee-brown), or *pleonaste* (green). These minerals usually build irregular rounded grains. In some of the rocks *perofskite* is a characteristic mineral, in minute crystals[1].

FIG. 24. PŒCILITIC STRUCTURE IN HORNBLENDE-PICRITE, MYNYDD PENARFYNNYDD, CAERNARVONSHIRE ; × 20.

The large plate enclosing olivine-grains and filling the field is a single crystal of hornblende. It is mostly colourless, but becomes deep brown in capriciously arranged patches round the edge [725].

A basic *felspar* occurs in many of the picrites[2], and in a special type of ultrabasic rock to be noticed below it becomes the dominant constituent; but it is wanting in the more typical peridotites. Some types have accessory garnet, which is always the magnesian variety *pyrope,* red-brown in slices.

[1] *Cf.* G. H. Williams on the serpentine of Syracuse, N. Y., *A. J. S.* (1887) xxxiv, 140–142.

[2] The original picrite of Tschermak has labradorite, but the felspar which occurs as an accessory in some peridotites is anorthite or bytownite.

Metallic *nickeliferous iron* occurs in some of the meteoric peridotites, besides special minerals, such as troilite.

Structure. The constituents follow, as a rule, the normal order of crystallization, the olivine constantly preceding the bisilicates. In many picrites, and in other types not too rich in olivine, the more or less rounded crystals of olivine are enclosed by large plates of pyroxene or hornblende (*pœcilitic* structure[1], fig. 24). When felspar occurs as an accessory, it is interstitial, but in the hornblende-picrites it may be embraced in ophitic fashion by part of the hornblende. In rocks consisting essentially of olivine and felspar the latter is found to have crystallized earlier when it is in preponderant quantity.

In the most basic peridotites the largely predominant olivine builds a granular aggregate, in which may be em-

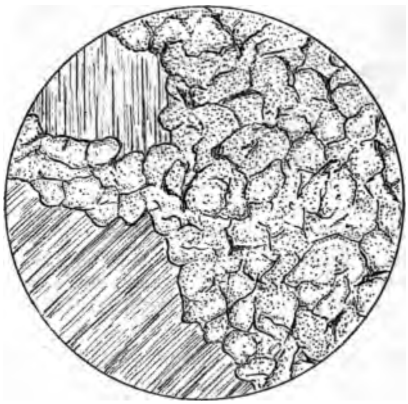

FIG. 25. ENSTATITE-PERIDOTITE WITH PSEUDO-PORPHYRITIC STRUCTURE, SKUTVIK, NEAR TROMSÖ, NORWAY; × 20.

Here olivine is largely in excess, forming a granular aggregate in which are imbedded large irregular crystals of a yellowish partly altered enstatite [440].

[1] This is quite analogous to the ophitic structure of dolerites *etc.* See G. H. Williams, *A. J. S.* (1886) xxxi, 30, 31; *Journ. of Geol.* (1893) i, 176.

bedded, with a *pseudo-porphyritic* appearance, relatively large crystals of enstatite, *etc.* (fig. 25). Any true porphyritic structure (*i.e.* some constituent occurring in two distinct generations) is rare in this family of rocks, the minerals usually forming an even-grained aggregate.

The pyrope-bearing peridotites often show a special type of structure, each garnet-crystal being surrounded by a broad border or shell known as *celyphite*[1] (Ger. Kelyphit). This border is sharply divided from the garnet, and possesses a marked radial fibrous structure. The name is not applied to any particular mineral, and the so-called celyphite is not always of the same constitution. A pale or colourless augite is common, while brown hornblende and enstatite are sometimes found, and brown picotite frequently accompanies the pyroxene. Again, brown biotite and magnetite have been observed[2]. A celyphite-border round garnet is also a characteristic feature in pyroxene-garnet-rocks (eclogites). Some petrologists have regarded it as a secondary 'reaction-rim,' but there seems to be no decisive reason for rejecting the primary origin of the growth.

Most of the meteoric peridotites have a peculiar structure termed *chrondritic*[3]. A fine-grained matrix of olivine, enstatite, chromite, *etc.*, encloses numerous round grains (*chondri*) consisting of the same minerals. In these chondri the crystals very commonly have a tendency to diverge from a point on the circumference.

Leading types. Numerous examples of rocks rich in olivine are known from the old gneiss area of Sutherland, from the western islands of Scotland, from North Wales, Cornwall, *etc.* There are frequent transitions from felspar-bearing picrites to thoroughly ultrabasic peridotites[4].

[1] Rosenbusch-Iddings, pl. XIV, fig. 4; Cohen (3), pl. LXI, fig. 2.
[2] Diller, *A. J. S.* (1886) xxxii, 123: *Bull. No.* 38 *U. S. Geol. Sur.* (1887) 15–17.
[3] For figures see Wadsworth's *Lithological Studies*; Lockyer, *Nature* (1890) xli, 306, 307; Farrington, *Journ. Geol.* (1901) ix, 174–180.
[4] For figures of several of these rocks, see Teall.

Good examples of *hornblende-picrite*, connected by transitional varieties with basic diorites, are found at Penarfynnydd[1], in the southwest of Caernarvonshire, and at several localities in Central Anglesey[2]. The hornblende is either deep brown or colourless, in the same crystal, and it encloses the rounded grains of olivine with typical pœcilitic structure (fig. 24). A colourless augite and a deep brown biotite occur, with a little original magnetite. Part of the hornblende is formed at the expense of augite. Anorthite is often present, usually embraced by the hornblende. Secondary crystal outgrowths from the primary hornblende are often seen[3].

G. H. Williams[4] has given an interesting account of hornblende-picrites from the Cortlandt district on the Hudson River. They resemble very closely the British examples and a well-known rock from Schriesheim, near Heidelberg[5], the bleaching of the brown hornblende and subordinate brown biotite being a characteristic feature. Examples from Alabama[6] have either brown or very pale green hornblende, and contain abundant pleonaste. One from Montana[7] has accessory hypersthene. Dr Bonney[8] has described a hornblende-picrite from Swift's Creek, Gippsland, Victoria.

An *augite-picrite* of Carboniferous age is found at Inchcolm[9], near Edinburgh, in which the dominant coloured mineral is a purplish-brown pleochroic augite, often with hourglass structure[10]. Deep brown hornblende is also present, chiefly as a marginal intergrowth with the augite. Felspar

[1] *Q. J. G. S.* (1888) xliv, 454–457. *Bala Volc. Rocks of Caern.* 99–101.

[2] Bonney, *Q. J. G. S.* xxxvii (1881) 137–140; xxxix (1883) 254–259. Also a similar rock from Alderney, *ibid.* (1889) xlv, 384; and one with pale biotite from Sark, *G. M.* 1889, 109–112.

[3] Teall, pl. VI.

[4] *A. J. S.* (1886) xxxi, 31–37; and in Diller, 294–297; *cf.* Bastin, *Journ. Geol.* (1906) xiv, 183–186 (Penobscot, Maine).

[5] For coloured plate see Berwerth, *Lief.* III.

[6] Clements, *Bull. No. 5 Geol. Sur. Ala.* (1896) 155–160.

[7] Merrill, *Proc. U. S. Nat. Mus.* (1894) xvii, 654.

[8] *M. M.* (1884) vi, 54.

[9] Cole's *Stud. Micro. Sci.* (1882) No. 6; Teall, pl. IV, fig. 2, VII; *20th Cent. Atlas*, 7–10, with plate.

[10] The augite resembles that of some nepheline-dolerites, and the rock differs in other respects from true plutonic types.

and biotite are subordinate. Most of the olivine is converted into a yellow serpentine. Augite-picrites with typical pœcilitic structure occur in Shropshire[1]. Busz has described an augite-picrite with comparatively fresh olivine from Highweek, near Newton Bushel, Devonshire: this has subordinate enstatite and biotite. Among examples from the Inner Hebrides Prof. Judd[2] notes one from the Shiant Isles with fine pœcilitic structure. Others occur in the Cuillin Hills in Skye[3] and in the Isle of Rum, graduating into more typical peridotites.

Intrusions of *enstatite-picrite* occur in the old gneiss of the west of Sutherland. In one near Lochinver the slightly pleochroic enstatite or bronzite is moulded on the olivine, but shows good crystal-faces, being enclosed by large crystal-plates of felspar. There is a subordinate colourless augite and some brown hornblende, which is partly formed from the pyroxenes, partly original and later than the felspar. This rock is almost as much a norite as a picrite, but true enstatite-peridotites also occur in the district, consisting of about equal parts of olivine and a rhombic pyroxene, with grains of pleonaste (fig. 26).

Of *mica-peridotite* few examples are described. One from Elliott County, Kentucky[4], consists of serpentinized olivine and pale yellow-brown to colourless mica, with pœcilitic arrangement, besides crystals of perofskite, *etc.* Sears[5] records a mica-peridotite from Andover in Massachusetts. Prof. Judd[6] has described under the name 'scyelite' a *hornblende-mica-peridotite* from the borders of Sutherland and Caithness (Loch Scye and Achavarasdale Moor). Here serpentinized grains of olivine are enclosed in pœcilitic fashion by a pale green to colourless hornblende, probably pseudomorphous after diallage, and a peculiar yellow mica. In Bengal[7] there are mica-peridotites remarkably rich in apatite (up to 11 *per*

[1] Watts, *Rep. Brit. Ass.* for 1887, 700; *Proc. Geol. Ass.* (1894) xiii, 340, fig.
[2] *Q. J. G. S.* (1885) xli, 393, pl. XIII, fig. 4
[3] *Tert. Ign. Rocks of Skye*, *Mem. Geol. Sur.* (1904) chap. vi.
[4] Diller, *A. J. S.* (1892) xliv, 286–289.
[5] *Bull. Essex Inst.* (1894) xxvi.
[6] *Q. J. G. S.* (1885) xli, 401–407; see also Teall, pl. v, fig. 2.
[7] Holland, *Rec. Geol. Sur. Ind.* (1894) xxvii, 129–141, pl. II.

cent.). From the Chalk Hills[1], near Salem, Madras, comes a variety consisting of diopside, olivine and biotite, the last with interstitial occurrence. Merrill[2] has described a diallage-mica-peridotite from Montana.

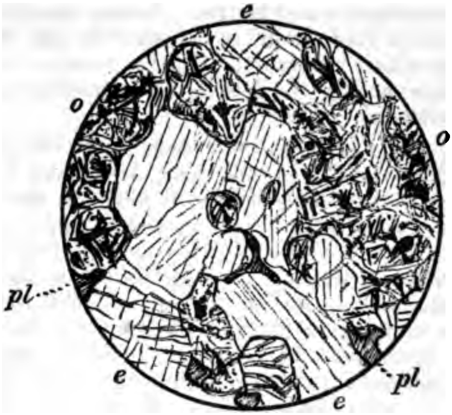

FIG. 26. ENSTATITE-PERIDOTITE, ASSYNT LODGE, SUTHERLAND; × 20.

A granular aggregate of olivine (*o*), largely serpentinized, and a slightly pleochroic enstatite or bronzite (*e*). These two minerals are in about equal quantity; in addition there are little irregular grains of isotropic green pleonaste (*pl*) [1642].

Augite-peridotite is represented among the Tertiary eruptives of western Scotland[3]. One from the Isle of Rum shows fresh olivine set in a framework of green augite. Magnetite and chromite are accessories, and sometimes hypersthene. In America augite-peridotites have been described from Little Deer Island[4] in Maine, *etc.* A porphyritic bronzite-diallage-peridotite occurs in Maryland[5], and a similar

[1] Middlemiss, *Rec. Geol. Sur. Ind.* (1896) xxix, 35.
[2] *Proc. U. S. Nat. Mus.* (1888) xi, 192–195.
[3] Judd, *Q. J. G. S.* (1885) xli, 389–395; Harker, *Tert. Ign. Rocks of Skye, Mem. Geol. Sur.* (1904) chap. vi.
[4] Merrill, *Proc. U. S. Nat. Mus.* (1888) xi, 192–195.
[5] G. H. Williams, *Amer. Geol.* (1890) vi, 38, 39, pl. II, fig. 1.

rock in Colusa County, California[1]. Some of these rocks, composed essentially of rhombic and monoclinic pyroxenes and olivine, approach the Lherz[2] type, from the Pyrenees. A rock of this type is described also from the Heazlewood district in Tasmania[3].

In some *enstatite-peridotites* the rhombic pyroxene is abundant, and forms a framework in which the somewhat rounded grains of olivine are set with pœcilitic structure. A well-known representative comes from the Harz (Baste or Harzburg type)[4], where, however, both minerals are more or less completely serpentinized. A similar rock is described from Presque Isle, Michigan[5].

In another type olivine largely predominates, and the enstatite occurs in relatively large crystals, which, among the smaller grains of olivine, give a pseudo-porphyritic appearance to the rock (fig. 25). Such rocks have been described from Inyo County, California[6], from the Heazlewood district in Tasmania[7], and from the Red Hill and Olivine Ranges in the South Island of New Zealand[8]. The last is interesting as carrying grains of a nickel-iron alloy (awaruite). From localities in Maryland, Williams[9] has described similar rocks in which large crystals of bronzite or diallage, or both, are embedded in a granular mass, mainly of olivine.

From these rocks it is only a step to one composed wholly of olivine, with only a little accessory picotite or chromite. Of this pure *olivine-rock* the type comes from New Zealand (Mount Dun), and is the 'dunite' of Hochstetter[10]. In Skye

[1] Wadsworth, *Lith. Stud.*, pl. v, figs. 1–3.

[2] See Bonney, *G. M.*, 1877, 59–64, and for coloured figures Teall, pl. I, fig. 1; Fouqué and Lévy, pl. LII, fig. 1.

[3] Twelvetrees and Petterd, *Proc. Roy. Soc. Tas.* for 1897, 31 and fig. 1.

[4] Wadsworth, *Lith. Stud.*, 133, 134, pl. VIII, figs. 1, 2, 5; Fouqué and Lévy, pl. LIII, fig. 2.

[5] Wadsworth, *loc. cit.*, 136–138, pl. VII, figs. 3–5.

[6] *Ibid.* 132, pl. VI, fig. 4.

[7] Twelvetrees and Petterd, *Proc. Roy. Soc. Tas.* for 1897, 26, 27.

[8] Ulrich, *Q. J. G. S.* (1890) xlvi, 625–629, pl. XXIV.

[9] *Bull. No.* 28 *U. S. Geol. Sur.* (1886) 50–55; *Amer. Geol.* (1890) vi, 38, 39, pl. II, fig. 1.

[10] *Cf.* Sollas in *Rocks of C. Colville Peninsula*, vol. ii (1906), 193, 194, with plate (Hokitika River).

very beautiful examples come from the southern part of the Cuillin Hills, near Loch Scavaig. Here the only mineral in addition to olivine is one of the spinellid group, usually deep brown picotite but sometimes green pleonaste. The picotite is in good octahedra, the pleonaste usually in rather irregular grains. In America examples of dunite come from Franklin, Webster[1], and Corundum Hill[2], all in North Carolina, and from Western Massachusetts[3]. One from Tulameen River, British Columbia[4] contains native platinum.

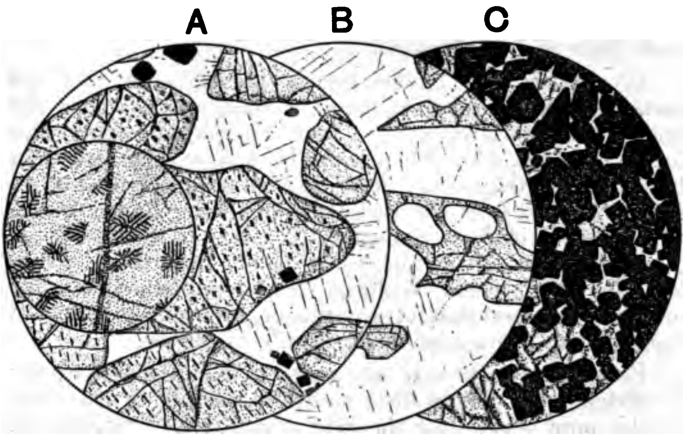

FIG. 27. ULTRABASIC ROCKS, INNER HEBRIDES; $\times 20$.

A. Anorthite-olivine-rock (Allival type), Allival, Rum. The abundant fresh olivine contains dendritic inclusions of magnetite, shown on a larger scale in the small inset circle ($\times$ 100). The opaque octahedra are of chromite [3521].

B. Another variety from the same locality; very rich in felspar, which is here idiomorphic towards the olivine [3532].

C. Dunite, a band very rich in picotite, Loch Scavaig, Skye: composed of deep brown picotite and olivine [2984].

[1] Wadsworth, *Lith. Stud.*, 118, 119, pl. IV, figs. 2, 3.
[2] Chatard, *Bull.* 42 *U. S. G. S.* (1887) 45.
[3] Martin, *A. J. S.* (1893) vi, 244–247.
[4] Kemp, *Bull.* 193 *U. S. G. S.* (1902) 44, pl. v, figs. *B*, *C*.

Typical dunite, with chromite, is found in the Chalk Hills[1], near Salem, Madras.

The Tertiary dunites of Skye[2] and Rum have a strongly banded structure, and some bands are extremely rich in a spinellid mineral, *viz.* chromite, picotite, or pleonaste in different examples (fig. 27, *C*).

In the varied ultrabasic rocks of Rum and Skye a felspar, always near anorthite in composition, is more abundant than pyroxene, and we may accordingly recognize *anorthite-peridotite* as a type locally of importance. In the mountains Allival and Askival, in Rum, the pyroxenic minerals often fail completely, and the rocks consist of olivine and felspar with some chromite or chrome-magnetite (Allival type, fig. 27, *A*). In different varieties the two principal constituents are found in all relative proportions, and it is noticeable that, where the felspar is predominant, it is idiomorphic towards the olivine (fig. 27, *B*).

Of *garnet-peridotites* that from Elliott County, Kentucky[3], is a good example. The pyrope crystals are surrounded by a 'celyphite' border of brown mica with an outer ring of magnetite-dust, these minerals being supposed to be due to a reaction between the garnet and the olivine.

Serpentine-rocks. Hitherto we have noticed only very briefly the secondary changes that affect the minerals of crystalline rocks. In the present family, however, the decomposition of a rock is often so complete that its original nature is detected only by careful study, and the altered rock-masses are commonly denoted by a special name, serpentine-rocks or simply serpentines, expressing their dominant mineral composition. The mineral serpentine is the commonest decomposition-product of the non-aluminous magnesian silicates (olivine, the rhombic pyroxenes, and some of the augites and hornblendes), and the purest serpentine-rocks result from the

[1] Middlemiss, *Rec. Geol. Sur. Ind.* (1896) xxix, 33.
[2] *Tert. Ign. Rocks of Skye, Mem. Geol. Sur.* (1904) 69–72.
[3] Diller, 290–294, pl. XXXIX; *A. J. S.* (1886) xxxii, 121–125; *Bull.* 38 *U. S. Geol. Sur.* (1887).

alteration of peridotites[1]. Other decomposition-products occur in the rocks, *viz.* iron-oxides (magnetite and limonite), steatite, carbonates (dolomite, *etc.*), chlorite, and tremolite; but the bulk is serpentine of various kinds, in which may be found undestroyed relics of the original minerals of the peridotite (olivine, diopside, pyrope, chromite, *etc.*).

Of the mineral serpentine some kinds are crystalline and doubly refracting, with interference-colours like quartz or felspar, and show faint pleochroism when the green tint is sufficiently pronounced. The habit is fibrous (chrysotile) or scaly (antigorite, *etc.*). Other kinds are amorphous and sensibly isotropic. Much of the serpentine occurs in definite pseudomorphs, and often retains something of the structure of the parent mineral to indicate its source. We may distinguish four cases:

(i) Serpentine derived from olivine, with the '*mesh-structure*[2]' (Tschermak's 'Maschenstructur'; see p. 80 and fig. 28).

(ii) Serpentine derived from enstatite or bronzite, in distinct pseudomorphs with the *bastite-structure* (see p. 79 and fig. 28).

(iii) Serpentine derived from a non-aluminous hornblende, with '*lattice-structure*[3]' ('Gitterstructur' of Weigand). Here the cleavage of the hornblende is marked by veins of birefringent serpentine in two sets making the characteristic angle $55\frac{1}{2}°$. This serpentine is minutely fibrous, with the fibres set perpendicularly to the cleavage of the hornblende. The rest of the pseudomorph is of serpentine giving no definite crystalline reaction and consisting probably of a confusedly fibrous aggregate.

(iv) Serpentine derived from a non-aluminous augite, with '*knitted-structure*[4]' ('gestrickte Structur' of Hussak). This consists chiefly of serpentine with scaly habit (antigorite). The scales give straight extinction and low polarization-tints.

[1] For descriptions and coloured figures of numerous serpentine rocks, see Wadsworth, *Lithological Studies* (1884). For a general sketch of observations and opinions on serpentine, see Teall, chap. vi.

[2] Cohen (3) pl. LXII, fig. 1.

[3] *Ibid.* fig. 3. [4] *Ibid.* fig. 4.

They occur in two closely interlacing sets parallel to the cleavage-planes of the augite, and so making an angle of about 87° with one another[1].

The source of serpentine in rocks can often be made out by these various characters, and it is placed beyond doubt when any unaltered relics of the parent mineral remain. In addition there may be serpentine encroaching upon contiguous minerals or traversing them in veins: this is, as a rule, sensibly isotropic.

The best-known serpentine-rocks in this country are those of the Lizard district in Cornwall[2]. The purer examples consist essentially of serpentine of various kinds, secondary iron-ore (often peroxidized), steatite, tremolite, *etc.*, and often undestroyed relics of olivine or other original minerals of the peridotites. Dr Bonney has shown that much of the serpentine has the character of that derived from olivine, and some of the original rocks were probably nearly pure olivine-rocks (Dun type). Others were enstatite- or bronzite-peridotites, and show large bastite-pseudomorphs after a rhombic pyroxene (Cadgwith, Coverack, *etc.*, fig. 28; *cf.* fig. 21)[3]. Others again are altered hornblende-peridotites, some of the serpentine showing the mesh- and some the lattice-structure, while relics of olivine, hornblende, and picotite may remain (Mullion Cove, Kynance Cove, *etc.*)[4]. Augite-picrites are also represented (Menheniot[5], *etc.*). Here felspar has been altered into a substance resembling serpentine, which Dr Teall thinks is probably that called pseudophite. Tremolite has been formed at the expense of olivine. The augite of the original rock is often preserved. Dr Bonney and Gen. McMahon[6], summarising the features of the Lizard serpentines, say that they "can be roughly separated into two groups: in

[1] Dr Bonney and Miss Raisin have rejected this interpretation of the lattice-structure; *Q. J. G. S.* (1905) lxi, 690–714, pl. XLV.

[2] Bonney, *Q. J. G. S.* (1877) xxxiii, 915–923; and (1883) xxxix, 21–23; Teall, 115 *et seqq.*

[3] See also Teall, pl. I, fig. 2; Cole's *Stud. Micro. Sci.* (1883) No. 50; *20th Century Atlas*, 43, with plate.

[4] See Teall, pl. XV.

[5] *20th Cent. Atlas*, 23, 24, with plate.

[6] *Q. J. G. S.* (1891) xlvii, 466.

the one a foliated mineral of the enstatite group is a conspicuous accessory; in the other a colourless augite or hornblende, usually the latter. A few are non-porphyritic[1], and in some cases exhibit no certain traces of any pyroxenic mineral, rhombic or monoclinic, though of course a spinellid or some iron oxide is always to be detected, and in one instance (at the Rill, W. of Kynance Cove) the presence of a fair proportion of felspar has been asserted[2]."

FIG. 28. SERPENTINE-ROCK, COVERACK, CORNWALL; × 20.

A large bastite-pseudomorph after bronzite is seen on the right. The rest of the rock is of serpentine with mesh-structure, derived from olivine: it is stained in places with hydrated iron-oxide [1118].

Various serpentinous rocks are found near Holyhead and in neighbouring parts of Anglesey. In rocks at Four-mile Bridge much of the serpentine has the character of that derived from augite, and the parent-rock seems to have been genetically connected with a gabbro mass. Mr Blake, however, found indications of olivine- and enstatite-serpentine[3].

[1] In the sense of containing no conspicuous crystals.

[2] Teall, p. 119. "The original rock, therefore, was of the nature of a picrite." See also *G. M.* 1887, 137, 138.

[3] *Rep. Brit. Ass.* for 1888, 408.

Of the numerous serpentine-rocks of Scotland[1], one at Balhamie Hill in Ayrshire has been described by Dr Bonney[2] as an altered olivine-bronzite-rock, closely resembling that of Cadgwith in Cornwall, the structure being of the pseudo-porphyritic type. Some near Belhelvie in Aberdeenshire[3] have also been enstatite-peridotites, but with the pœcilitic structure, and now show pseudomorphs after olivine set in a framework of bastite, just as in the rock of Baste in the Harz, which has given its name to the latter mineral.

In the eastern United States numerous serpentine-rocks, some derived from peridotites, others from pyroxenites, occur along the 'Piedmont belt' from North Carolina to New York. The rock at Syracuse, N.Y., was shown by Williams[4] to be an altered peridotite, sharply defined pseudomorphs after olivine and enstatite being easily detected, while the remaining constituents, *viz.* brown mica, perofskite, and chromite, are still preserved. Wadsworth has described peridotite-serpentines from Minnesota[5], from Plumas County, California, from Westfield and Lynnfield, Mass., and other localities[6]. Near San Francisco occur some derived from peridotites (the Potrero[7]), others from pyroxene-rocks (Angel Island[8]). The derivation of serpentine from pyroxene is very clearly exhibited in some American occurrences described by Merrill at Montville, N.J.[9] and in Essex County[10] and Warren County[11], N.Y.

Serpentine-rocks, derived from peridotites very rich in olivine, are widely distributed in the South Island of New Zealand[12].

[1] For coloured plate of Portsoy serpentine see Cole's *Stud. Micro. Sci.* No. 52.

[2] *Q. J. G. S.* (1878) xxxiv, 770.

[3] Bonney, *G. M.* 1885, 440.

[4] *A. J. S.* (1887) xxxiv, 140–142. For other serpentines from New York State see Newland, *Sch. of Mines Quarterly* (1901) xxii, 307–317, 399–410.

[5] *Prelim. Descr. Perid. Gabb. etc. Minn.* (1887) 29, pl. I, fig. 1.

[6] *Lithological Studies* (1884) 158–160, pl. VI, figs. 2, 5, VII, fig. 2.

[7] Palache, *Bull. Geol. Dep. Univ. Cal.* (1894) i, 165–169.

[8] Ransome, *Ibid.* (1894) i, 220–222.

[9] *Proc. U. S. Nat. Mus.* (1888) xi, 105–111, pl. XXXII.

[10] *Ibid.* (1889) xii, 595–599.

[11] *A. J. S.* (1889) xxxvii, 189–191.

[12] Sollas in *Rocks of C. Colville Peninsula*, vol. ii (1906) 185, 186, with plate; also *Bull.* 1 (*N. S.*) *N. Z. Geol. Sur.*, 69, 79 (Westland).

B. HYPABYSSAL ROCKS.

SOME petrologists are content to divide the igneous rocks into two great groups, according as their structural characters indicate consolidation under deep-seated or under superficial conditions. Others, however, recognize another group intermediate between these two. Thus Rosenbusch inserts between his 'Tiefengesteine' and 'Ergussgesteine' a group 'Ganggesteine' or 'dyke-rocks.' The rocks to be treated under the present head correspond in a general way, though not precisely, with the last named, but Brögger's name 'hypabyssal' is adopted as more accurately expressing the characters upon which the group is founded.

Although this threefold division seems to be necessitated by a comparative study of the great variety of rock-types met with in nature, it must be admitted that the hypabyssal group is a somewhat artificial one, the rocks included in it lacking any well defined set of common characteristics distinguishing them from the other two groups. Any definition would have to be framed chiefly in negative terms, and would bring together types presenting many points of difference from one another. Most of them are holocrystalline, but in some a glassy residue is found. In some families the porphyritic structure is characteristic[1], as it is in the volcanic rocks; in others it is wanting or non-significant: but even the holocrystalline non-porphyritic types have structural and mineralogical characters, to be noted below, which differentiate them from rocks of truly deep-seated origin.

[1] On the significance of this structure see Cross, 14*th Ann. Rep. U. S. Geol. Sur.* (1895) 232–235; Pirsson, *A. J. S.* (1899) vii, 271–280; Crosby, *Amer. Geol.* (1900) xxv, 299.

CHAPTER VII.

ACID HYPABYSSAL ROCKS.

THE acid hypabyssal rocks embrace a considerable range of varieties, bridging over the difference between the even-grained, holocrystalline granites and the porphyritic, largely glassy rhyolites. The porphyritic character is almost universal, but the ground-mass which encloses the phenocrysts may be holocrystalline, partly crystalline and partly glassy, or wholly glassy. On the nature and special structures of the ground-mass depend chiefly the several types usually recognized among these rocks. All agree in that the constituent minerals—in so far as these are developed—include in the first rank felspars rich in alkali and usually quartz, while ferro-magnesian minerals and free iron-ores occur only in relatively small quantity, and are sometimes wanting.

On examination of their mineral constitution and characteristic structures, the more crystalline types are readily referred to their proper positions; but, in proportion as the bulk of the rock comes to consist of unindividualised glassy matter or an irresolvable cryptocrystalline 'base,' the criteria become fewer. In particular, the first stage of consolidation (that of the phenocrysts) may have been arrested before quartz (the last mineral) began to crystallize, and so, if the ground-mass consolidates as a glass, we may have a thoroughly acid rock without quartz. Thus the most glassy rocks (pitchstones) belonging to this family are not always to be distinguished by the microscope alone from less acid pitchstones. Again, they are scarcely divided from some glassy rhyolites (obsidians).

The nomenclature of these acid rocks is confused. The name 'felsite' or—if containing evident phenocrysts of quartz—'quartz-felsite' has been applied in this country not only to these rocks but also to many volcanic rocks (acid and intermediate), and its usage lacks precision and significance. The name quartz-porphyry, borrowed from the German, covers most of the rocks, but not all, since porphyritic quartz may be wanting: this term is also used by Continental writers for the 'older' acid lavas. For a type rich in soda, and having some mineralogical peculiarities, the name quartz-ceratophyre (Ger. Quarzkeratophyr) has been used. It will be convenient to speak of the family, as a whole, as the acid intrusives. The names applied to particular types will be noticed in connection with the ground-mass.

Constituent minerals. We notice here especially the minerals occurring as phenocrysts. Of these, the felspars include *orthoclase* (not microcline) and an acid plagioclase such as *oligoclase*. The two are commonly associated, and both build idiomorphic crystals with the usual types of twinning. A narrow zone of orthoclase surrounding each plagioclase crystal is seen in some rocks. The characteristic felspar of the quartz-ceratophyres is *anorthoclase*.

The *quartz* has crystallized in the ordinary hexagonal pyramids, sometimes with narrow prism-faces, but the crystals are frequently rounded and eaten into, owing to corrosion by the ground-mass, and may have lost all crystal outlines. In the rock-types most nearly approaching granites (granite-porphyries) the quartz contains fluid-pores: in other types the inclusions are mostly of glass or portions of the ground-mass (fig. 29, *A*). As already mentioned, quartz-phenocrysts are not always present.

The brown *biotite*, which occurs in many of the rocks, has the same characters as in granites, and carries the same inclusions. It is usually in good hexagonal flakes. Less commonly, in the marginal part of an intrusion, it has a blade-like habit, due to extension along the *a*-axis. The usual mode of alteration is chloritization. Hexagonal flakes of *muscovite* are found in a few of the granite-porphyries only,

A green *hornblende* in well-built crystals is a rather exceptional constituent. The deep blue soda-bearing amphibole *riebeckite* occurs in a few rocks, always in very ragged allotriomorphic crystals (fig. 29, *B*). The *augite* of the acid

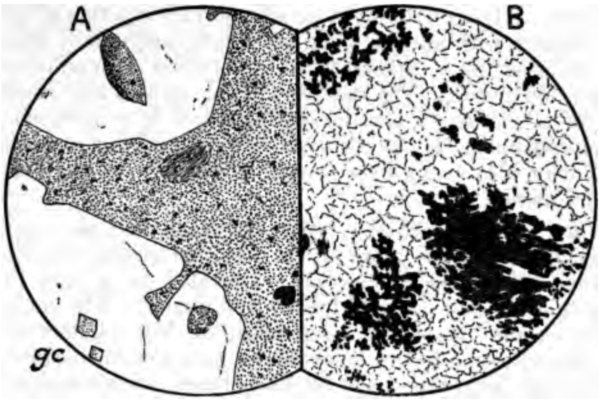

Fig. 29. × 20.

A. Quartz-porphyry, dyke, King's Cave, Arran. The quartz-phenocrysts are partly corroded, and contain inclusions of the ground-mass, as well as relatively large glass-cavities (*gc*) with the form of 'negative crystals' [3151].

B. Riebeckite-Microgranite ('paisanite'), Mynydd Mawr, Caernarvonshire. The nearly opaque crystals of sponge-like form are the dark blue soda-amphibole, riebeckite [2750].

intrusives is a pale greenish variety like that in some granites, but occurs here much more frequently. It builds good idiomorphic crystals in many granophyres and pitchstones. A few rocks rich in soda contain *ægirine*. A rhombic pyroxene (*bronzite*) is also known.

As accessories, *apatite* and *zircon* are widely but sparingly distributed, while the iron-ores are usually represented only by a little *magnetite*. Such minerals as garnet, allanite, and pinite pseudomorphs after cordierite[1] occur in special

[1] Fouqué and Lévy, pl. xiii, fig. 5.

localities. Some granite-porphyries carry *tourmaline* (Cornwall; Elba).

Ground-mass and structures. The types which approach most nearly to the plutonic habit are known as *granite-porphyry*. Here relatively large idiomorphic crystals of quartz and felspars, with mica or some other ferro-magnesian mineral, are enclosed in a fine-textured crystalline ground-mass of felspar and quartz. The structure of this ground may resemble that of a granite, or may be distinguished by a more marked idiomorphism of the lath-shaped felspars, usually untwinned. Mica may also occur in a second generation as part of the ground-mass.

Very common are the types in which the phenocrysts, consisting of felspars, more or less corroded quartz, and biotite or some other constituent, are embedded in a very finely crystalline ground-mass of felspar and quartz. The elements of the ground-mass may have more or less idiomorphism. Quartz-porphyries having an evidently microcrystalline ground-mass of this kind are styled by Rosenbusch *microgranites*, the porphyritic character being understood.

When the texture of the ground-mass sinks to such minuteness as to be not clearly resolved under the microscope, it may be described as *cryptocrystalline* ('microfelsitic' of some authors). For such rocks Rosenbusch uses the term felsophyre[1]. Without entering into a discussion of an obscure subject, it may be said that this cryptocrystalline ground is probably in some cases original, in other cases due to secondary change (devitrification) of a ground-mass originally glassy.

The glassy (or 'vitrophyric') type of ground-mass is seen in the rocks known as *pitchstones*. In some of these, phenocrysts of felspar, *etc.*, are only sparingly present, the great bulk of the rock consisting essentially of isotropic glass. This glassy ground, however, includes in many cases innumerable minute and imperfectly developed crystalline growths (*crystallites*) with regular grouping (fig. 32). These minute bodies will be more fully noticed in connection with the acid lavas. The pitchstones frequently show perlitic cracks, and occasionally

[1] *Cf.* Teall, *G. M.* 1885, 108–111.

some of the flow-phenomena which are better exhibited in lavas. Typical pitchstones, excluding lava-flows, are of quite limited distribution.

In the above types we have what may be regarded as a graduated transition from the granitic to the rhyolitic structures, the only gap, that between cryptocrystalline matter and glass, being one which the instruments at our disposal do not enable us to bridge. There is, however, a second, more or less distinct, line of transition, parallel to the former but characterized by a different set of structures, *viz.* micrographic intergrowths of felspar and quartz and regular radiate aggregates of felspar fibres. To these structures Rosenbusch applies the somewhat inappropriate term 'granophyric,' including both micropegmatitic and microspherulitic: and the rocks having a ground-mass of this nature are very generally known as *granophyres*.

We have already noticed in some granites a micrographic intergrowth of the kind named micropegmatite; but when the whole mass of the rock, exclusive of crystals of certain minerals, takes on this character, we have a type characteristic of hypabyssal rather than abyssal rocks as here understood. In such rocks the quartz and the greater part of the felspar form a micrographic ground-mass, which may enclose idiomorphic crystals of some ferro-magnesian mineral (augite or biotite) or of felspar (mostly plagioclase). Further, the micrographic intergrowth may come in to some extent in rocks which on the whole would be placed with the granite-porphyries or the micrograiitic type. When the intergrowth is on a relatively coarse scale, it is often rude and irregular, but the finer-textured '*micropegmatite*' shows great regularity and often a definite arrangement[1] (fig. 30, *A*). In particular it frequently forms a regular frame surrounding phenocrysts of felspar[2], and it can often be verified that the felspar of the intergrowth is in crystalline continuity with the felspar crystal which served as a nucleus (fig. 30, *B*). The appearance is as if the original crystal had continued to grow

[1] Cohen (3), pl. XXXIII.

[2] For good illustrations see Irving, *Copper-bearing Rocks L. Superior*, pl. XIV, figs. 1, 2.

throughout the final consolidation of the rock, enclosing the residual excess of silica as intergrown quartz. Sometimes a line of Carlsbad twinning can be traced from the crystal through the surrounding frame. There is no doubt that

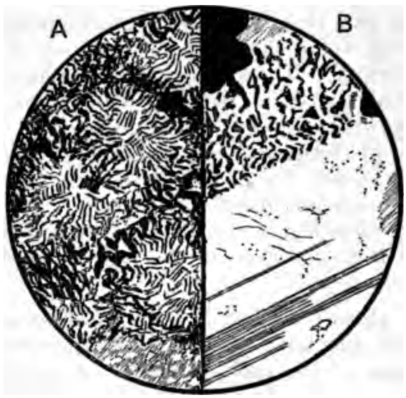

FIG. 30. GRANOPHYRES, SHOWING MICROGRAPHIC INTERGROWTH OF FELSPAR AND QUARTZ; × 20, CROSSED NICOLS.

A. Crug, near Caernarvon: showing an intricate aggregate of rather delicate micropegmatite with a tendency to irregular 'centric' arrangement [17]. *B*. Carrock Fell, Cumberland, showing part of a phenocryst of oligoclase with a fringe of micropegmatite. The felspar in this is in crystalline continuity with the phenocryst; the quartz, shown in the position of extinction, is continuous with a quartz-grain at the top of the figure [1545].

plagioclase felspar, as well as orthoclase, enters into such micrographic intergrowths. Less frequently the quartz of the intergrowth is seen to be in crystalline continuity with a quartz crystal or grain, upon which it has grown.

The finest micrographic intergrowth tends especially to a stellate or radiate ('centric') arrangement, with or without a nucleus of an earlier crystal. As the growth becomes very delicate in texture, the sectors within which the felspar extinguishes simultaneously become narrower, and are represented between crossed nicols by dark rays when their

direction makes a small angle with one of the cross-wires. When the structure is on too minute a scale to be resolved by the microscope, it may be termed, by analogy, cryptographic. The optical characters of such an aggregate appear to be determined by the minute radially arranged fibres of felspar, which obscure the quartz. The structures known as *micro-spherulitic* and pseudo-spherulitic in acid rocks are probably of this nature (fig. 31). Between crossed nicols they show

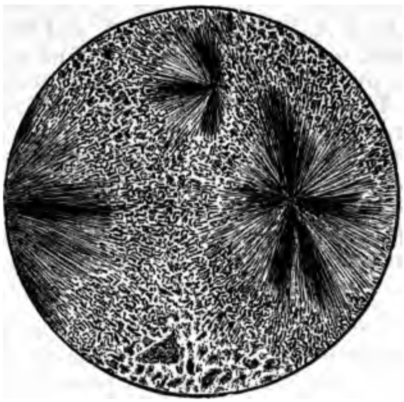

FIG. 31. SPHERULITIC GRANOPHYRE, GLAS-BHEINN BHEAG, SKYE; × 20, CROSSED NICOLS.

The spherulites (pseudospherulites of some authors) consist of a cryptographic intergrowth of felspar and quartz arranged radially about centres. At the periphery of each spherulite the cryptographic passes into a visibly micrographic structure, and the radial arrangement becomes less marked. Between the spherulites are interspaces in which the structure is granular [2494].

characteristically a black cross, caused by extinction in those fibres which lie nearly parallel to one of the cross-wires. Such growths cluster round porphyritic crystals of quartz or felspar, or, as innumerable closely packed minute spherules, constitute almost the whole of the ground-mass[1].

[1] For good figures of micrographic and cryptographic structures, ranging from the micropegmatitic to the spherulitic, see Fouqué and

Isolated spherulites or bands of spherulites may occur in a vitreous or devitrified ground.

Leading types. We proceed to select a few examples illustrating the several points indicated above. In view of the frequent association of the different types of ground-mass in one district, or even in parts of one intrusion, we shall not find it convenient to follow any strict order.

The Carboniferous 'elvan' dykes of Cornwall and Devon, as described by J. A. Phillips[1], Dr Teall, and Dr Flett, have a microcrystalline to cryptocrystalline ground-mass, enclosing large felspars, pyramidal or rounded quartz crystals, and often two micas. The quartz contains either glass-inclusions[2] or fluid-pores, sometimes in the form of negative crystals[3], which may enclose a salt-cube as well as a bubble[4]. Tourmaline is of frequent occurrence in crystals or stellate groups of needles, and is sometimes seen to replace felspar. An occasional constituent is cordierite, represented by the so-called 'pinite' pseudomorphs of yellowish green micaceous flakes (Sydney Cove[5]).

The varied group of Ordovician intrusive rocks in Caernarvonshire[6] include some *granite-porphyries* of a well-marked type. Quartz is wanting among the phenocrysts, which are chiefly of oligoclase. One example at the head of Nant Ffrancon has a ground-mass of allotriomorphic quartz and felspar (chiefly orthoclase). The ferro-magnesian constituent is biotite. Others, quarried at Yr Eifl and near Nevin, have a ground-mass of idiomorphic felspars and interstitial quartz. These contain augite, usually without biotite. Other rocks in the district, all augitic, show more or less tendency to

Lévy, pl. x, fig. 2; xi, fig. 1; xii, xiv, xv, xvi. For cryptographic structure, see also Cohen (3), pl. xxxiv, figs. 3, 4, and chromolith. in Berwerth, *Lief.* iv (from Baden, compare micrographic rock from Vosges).

1 *Q. J. G. S.* (1875) xxxi, 334–338, pl. xvi; *cf.* Cohen (3), pl. xxii, fig. 1; Hill, *Summ. of Progr. Geol. Sur.* for 1901, 26; Flett, *Geol. Land's End, Mem. Geol. Sur.* (1907) 61–67.

2 Cohen (3), pl. ix, fig. 1.

3 *Ibid.* pl. xi, fig. 4.

4 *Ibid.* pl. xii, fig. 4.

5 Teall, 334.

6 *Bala Volc. Ser. Caern.* (1889) 48–56.

micrographic structures, and in many the whole ground-mass is of micropegmatite. Beautiful examples occur in the hills above Aber and at Moel Perfedd in Nant Ffrancon. The growth of the micropegmatite round felspar crystals is well exhibited, and in some cases a narrow zone of orthoclase is seen interposed between a plagioclase crystal and the surrounding growth. The structure is rarely so minute as to approximate to the spherulitic. Many of the smaller intrusions in the district, *e.g.* near Clynog-fawr, are of quartz-porphyry with a cryptocrystalline ground, which may possibly be due to devitrification. Porphyritic quartz, which is wanting in the more evidently crystalline types, appears here in corroded crystal-grains.

The complex group of acid rocks near Caernarvon and eastward, which some have supposed to be of pre-Cambrian age, affords examples of granite-porphyries, micrographic rocks (fig. 30, *A*), microcrystalline and spherulitic quartz-porphyries, *etc.* The spherulitic growths often surround pyramids of quartz. The porphyritic felspars in all these rocks are mostly plagioclase, and the ferro-magnesian mineral is biotite, often green from alteration. Various granophyres and, especially, beautiful spherulitic rocks, showing the growth round pyramidal crystals of quartz, occur at St David's[1]. The structure is of the cryptographic type, not showing a very perfect black cross.

The Lake District contains examples of *microgranites*, such as the rock quarried at Threlkeld, while some minor intrusions show a cryptocrystalline ground. Granophyres also occur, the large Buttermere and Ennerdale intrusion being of a micropegmatitic rock with either biotite or augite, resembling some Caernarvonshire examples[2]. The dykes of Armboth and Helvellyn have a spherulitic ground-mass enclosing idiomorphic crystals of quartz and felspar. The spherulitic growth, which does not always give a good black cross, is clustered especially about the quartz crystals. A few garnets occur. These rocks are probably all Ordovician. The Devonian dykes about Shap, in Edenside, near Sedbergh, *etc.*, have microcrystalline to cryptocrystalline grounds, and some of them contain biotite

[1] Geikie, *Q. J. G. S.* (1883) xxxix, 315, pl. x, figs. 8, 9.
[2] *Cf.* Rastall, *Q. J. G. S.* (1906) lxii, 258–260, 270, pl. XXVIII.

rather abundantly. An intrusion near Dufton Pike[1] in Westmorland is a characteristic granite-porphyry with white and dark micas, which occur both as phenocrysts and in the ground-mass. The other phenocrysts are idiomorphic quartz and felspar, chiefly plagioclase but with a few large sanidine-crystals.

One of the most beautiful *granophyres* in this country is that of Carrock Fell, in Cumberland[2]. It contains a pale augite in good crystals, often uralitized or otherwise altered, and rarely a little biotite. There are also idiomorphic felspars, usually oligoclase, and some granules of iron-ore. The ground-mass shows in different specimens, or even in one slide, every gradation, from a coarse irregular micropegmatite through exquisitely regular micrographic[3] and cryptographic structures to what would be described as spherulitic. These intergrowths usually make up the whole ground-mass, though sometimes part of the quartz forms irregular grains. The arrangement is sometimes 'centric,' but more usually peripheral to the felspar phenocrysts, forming a regular border to them. It can often be seen that the felspar of the intergrowth is continuous with that of the crystal, and much of it must be plagioclase (fig. 30, *B*).

The biotite-bearing *quartz-porphyries* of the Cheviots[4] have sometimes granophyric structures, but are more commonly micro- to cryptocrystalline. Frequently the ground-mass encloses patches of micropegmatite like porphyritic crystals, sometimes showing the outlines of idiomorphic felspar. This feature is also well shown in a microgranitic quartz-porphyry from the Black Hill in the Pentlands[5]. Among Scottish quartz-porphyries of Tertiary age those which form numerous sills and dykes in the Isle of Arran[6] are worthy of notice. The ground-mass is microcystalline in the larger intrusive bodies but often cryptocrystalline in the smaller (fig. 29, *A*).

1 *Q. J. G. S.* (1891) xlvii, 519.

2 *Ibid.* (1895) li, 126–129.

3 Teall, pl. XLVII, fig. 5 (misplaced 4 in key-plate).

4 Teall, *G. M.* 1885, 111; Kynaston, *Tr. Edin. G. S.* (1899) vii, 402–408, pl. XXV, figs. 2, 3; Teall, pl. XXXI, fig. 2.

5 Flett, *Tr. Edin. G. S.* (1899) vii, 483–486, pl. XXVII, figs. 2–4.

6 *Mem. Geol. Sur. Scot.*, *Geol. N. Arran* (1903) 109, 110.

More interesting are the well known and beautiful Arran *pitchstones*[1], of which some are of acid, others of subacid composition. They form dykes and sheets of Tertiary age. The phenocrysts are of sanidine, quartz, plagioclase, and augite, varying in different examples and sometimes occurring very sparingly. The ground-mass is of glass crowded with crystallites, which often assume peculiar groupings. In one variety needle-shaped microlites (belonites) of hornblende occur, each forming the trunk of a delicate arborescent aggregate of more minute bodies (Corriegills, fig. 32, *A* and *B*). In another variety occur crosses, each of the four arms carrying a plume-like growth (Tormore, fig. 32, *C*). Again, little rod-like bodies frequently occur as a fringe arranged perpendicularly on the faces of phenocrysts. The general mass of the glass is full of very minute crystallitic bodies, but round each grouping is a clear space, indicating that the tree-like or other growth has been built up at the expense of the surrounding part. Flow-structures are only occasionally met with, and perlitic cracks are not common. Dykes of pitchstone with various crystallitic growths occur also in Skye (Glamaig near Sligachan and Coirechatachan near Broadford)[2], on the south coast of Eigg, and in Donegal (Barnesmore Gap)[3]. All these British pitchstones are remarkable for their richness in ferro-magnesian crystallites, sometimes of hornblende, sometimes of augite. Some of the Arran pitchstones are of intermediate rather than acid composition. In some of the Eigg dykes, and in the sheet of porphyritic pitchstone which makes the Sgùrr in the same island[4], on the other hand, the abundant crystallites are of felspar. The large felspar crystals are of anorthoclase or cryptoperthite, and the other porphyritic elements are augite, enstatite, and magnetite.

The Eigg pitchstone dykes and certain of those in Arran afford good illustrations of devitrification.

[1] Allport, *G. M.* 1872, 1–9; 1881, 438; Bonney, *G. M.* 1877, 499–511; Judd, *Q. J. G. S.* (1893) xlix, 546–551, 559–561, pl. XIX; Teall, pl. XXXIV, figs. 3, 4; Cohen (3), pl. IV, fig. 1; *Geol. N. Arran*, 120–123; *20th Cent. Atlas*, 61, 62, with plate.

[2] *Mem. Geol. Sur., Tert. Ign. Rocks Skye* (1904) 403, 407, pl. XX, fig. 5; XXIV, fig. 3.

[3] Sollas, *Sci. Pr. Roy. Dubl. Soc.* (1893) viii, 87–91.

[4] Judd, *Q. J. G. S.* (1890) xlvi, 380.

The British Tertiary intrusions furnish also many examples of granophyres. The large granite masses of Skye, Mull, *etc.* often pass into micrographic modifications[1], and sometimes at the margin into cryptographic (fig. 31). But there are also many independent dykes and sheets, which are sometimes microgranitic quartz-porphyries but frequently granophyres[2]. The ferro-magnesian element, only sparingly present, is usually augite; but in some cases it is hornblende or biotite, as in examples from near Newcastle and Hilltown, Co. Down[3].

As illustrating a peculiar variety of structure, one rock from Corriegills in Arran[4] appears as if divided into polygonal

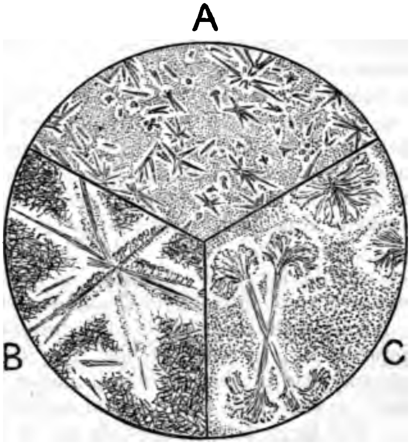

FIG. 32. PITCHSTONES, ARRAN.

A. Arborescent crystallites with stellate grouping, Corriegills; × 20 [2752].
B. The same; × 100.
C. Plumose crystallites with cross-like grouping, Tormore; × 100 [2751].

1 *Mem. Geol. Sur., Tert. Ign. Rocks Skye* (1904) pl. XIX, fig. 1; Teall, pl. XXXIII, fig. 1 (Mull).
2 *Tert. Ign. Rocks Skye*, 280–286, pl. XXII, fig. 1.
3 Hyland, *Sci. Proc. Roy. Dubl. Soc.* (1890) vi, 420–430.
4 Allport, *G. M.* 1872, 541; Bonney, *G. M.* 1877, 506–508; *20th Cent. Atlas*, 33, with plate; Teall, pl. XXXIX, fig. 1.

areas, each enclosing a spherule with well marked boundary and radial structure.

Acid intrusives rich in soda (quartz-ceratophyres) are not yet well known in this country. Probably some of the 'soda-felsites' of Leinster[1], of Ordovician age, are to be placed here. They are microcrystalline rocks, with or without porphyritic structure, consisting essentially of predominating felspar and quartz. Plagioclase is much more abundant than orthoclase, and is sometimes albite, sometimes possibly anorthoclase or cryptoperthite.

More remarkable are those rocks in which the ferro-magnesian minerals also are of soda-bearing varieties. From Mynydd Mawr, in Caernarvonshire, comes a rock (fig. 29, *B*) containing ragged riebeckite, with microperthitic felspars and some quartz-grains, in a ground-mass of quartz and felspar with microlites of some unknown mineral[2]. A somewhat similar rock occurs at Ailsa Craig[3], and both are closely allied to rocks from Texas mentioned below (Paisani type). An ægirine-bearing variety is represented in western Sutherland. Dr Teall[4] has described an example from Poll an Droighinn, near Inchnadamph, as consisting of polysynthetic aggregates representing original phenocrysts of alkali felspar, streaks of microcrystalline quartz (scarce), and a crypto- or micro-crystalline felspathic matrix crowded with acicular microlites of ægirine. This has very decided resemblance to an interesting type described by Brögger from the Christiania district (Grorud type), which, however, is of somewhat more acid composition, and richer in ægirine.

Among the numerous acid hypabyssal rocks occurring in America may be mentioned the hornblende-granite-porphyries described by Zirkel[5] for the Fortieth Parallel Survey. These

[1] Hatch, *G. M.* 1889, 70–73, 545–549.

[2] *G. M.* 1888, 225, 226, 455, 456; *Bala Volc. Ser. Caern.* (1889) 50–52.

[3] Teall, *M. M.* (1891) ix, 219–221; Heddle, *Tr. Edin. G. S.* (1897) vii, 266, pl. xv, fig. 1; Adye's *Stud. Micropetr.* 23, 24, pl. v, fig. 2. Riebeckite occurs also in the granophyre of Meall Dearg, in Skye; Teall, *Q. J. G. S.* (1894) l, 219; Harker, *Tert. Ign. Rocks Skye* (1904), 158, 159, 165.

[4] *G. M.* 1900, 391.

[5] *Micro. Petrogr. Fortieth Parallel* (1876) 62–67.

carry porphyritic quartz and felspars, plagioclase being prominent, hornblende, biotite, and often sphene, with a microcrystalline ground-mass. The quartz has fluid-pores sometimes containing salt-cubes and other inclusions[1]. Typical examples occur at Franklin Buttes, Nevada, in the Oquirrh Mts, Utah, *etc.* Rocks with cryptocrystalline ground-mass ('felsite-porphyry') also occur, though in less force[2], and spherulitic varieties are found (Spruce Mt, Peoquop Range). A granite-porphyry similar to the above has been described in detail by Iddings[3] from the Eureka district, Nevada; and Pirsson[4] has given an account of granite-porphyries, some with biotite, others with hornblende, from the Little Belt Mts, Montana. Quartz-porphyries carrying tourmaline occur in the Castle Mountain district, Montana[5], and in the Tintic Mts, Utah[6]. The quartz-porphyries of the Black Hills, S. Dakota, have been described by J. D. Irving[7]. Few typical pitchstones have been recorded in the United States. Osann[8] notices one from the Eagle Mts in Western Texas, which recalls the Arran rocks, containing stellate groupings of green augite crystallites.

In the Apache Mts, in the same district, Osann[9] has described a riebeckite-granite-porphyry (Paisani type), having scattered porphyritic felspars (microperthite) and quartz in a ground-mass containing ragged crystal-grains of riebeckite with microperthitic felspar and quartz. Washington[10] notes from Magnolia Point, Mass., a rock with a fine-textured ground-mass containing minute needles of greenish-blue glaucophane-riebeckite; and in another from Bass Rocks in the same district the coloured silicate is deep blue glaucophane[11]. Rocks more or less closely comparable with the Grorud type,

1 *Micro. Petrogr. Fortieth Parallel* (1876) 63, 77, pl. I, fig. 5.
2 *Ibid.* 73–80.
3 *Monog.* XX *U. S. Geol. Sur.* (1893) 339–345.
4 *20th Ann. Rep. U. S. Geol. Sur.* part III (1900) 491–511.
5 Weed and Pirsson, *Bull.* 139 *U. S. Geol. Sur.* (1896) 99–103.
6 Tower and Smith, *19th Ann. Rep. U. S. Geol. Sur.* part III (1899) 632.
7 *Ann. N. Y. Acad. Sci.* (1899) xii, 276–281.
8 *4th Ann. Rep. Geol. Sur. Tex.* (1892) 134.
9 *Ibid.* 131, 132.
10 *Journ. Geol.* (1899) vii, 111–113.
11 *Ibid.* 117, 118.

with abundant ægirine, are found in the Black Hills of Dakota[1] and at Judith Peak in Montana[2].

The common types of acid hypabyssal rocks are repeated in many parts of the world, and it is not necessary to particularise localities. Spherulitic granophyres, for instance, have been described from Bathurst[3] and Carcoar[4] in New South Wales, from the Noyang district of Victoria[5], and from the west coast of Tasmania[6].

[1] J. D. Irving, *Ann. N. Y. Acad. Sci.* (1899) xii, 248, 257.
[2] Pirsson, 18*th Ann. Rep. U. S. Geol. Sur.* part III (1898) 558, 559.
[3] Anderson, *Rec. Geol. Sur. N. S. W.* (1889) i, 16–22, pl. II, *A*.
[4] Curran, *Journ. Roy. Soc. N. S. W.* (1891) xxv, 218, 219.
[5] Howitt, *Tr. Roy. Soc. Vict.* (1884) xx, 43.
[6] Twelvetrees and Petterd, *Pr. Roy. Soc. Tas.* for 1897, 59–61, with plate.

CHAPTER VIII.

PORPHYRIES AND PORPHYRITES.

THE rocks which are for convenience grouped together in this chapter belong to various hypabyssal types of intermediate chemical composition. They have not a very wide distribution, and they graduate on the one hand into the acid intrusives already discussed, on the other into the more peculiar family of the lamprophyres.

The porphyritic structure characterizes almost all the rocks in question, and in most of the types is marked by felspar phenocrysts of relatively large size. The ferro-magnesian minerals are often confined to the elements of the earlier period of crystallization. Original quartz is found in the more acid types only, and is almost always restricted to the ground-mass.

The rocks may be regarded as standing between the plutonic syenites, diorites, *etc.*, on the one hand, and the volcanic trachytes, dacites, and andesites on the other, just as the rocks treated in the preceding chapter stand between the granites and the rhyolites. According as the dominant constituent is an alkali-felspar or a soda-lime-felspar, they fall into two families, to be distinguished as porphyries and porphyrites respectively. To these must be added the types distinguished by the presence of a felspathoid mineral in addition to alkali-felspar. These correspond in a general way with the plutonic nepheline-syenites, and may be considered to constitute a separate family.

Under the first head we may recognize *syenite-porphyry* and *orthoclase-porphyry* (with orthophyre), corresponding with granite-porphyry and quartz-porphyry among the acid rocks. From these orthoclase-bearing rocks have been separated others characterized by a potash-soda-felspar, under the name *ceratophyre* (Ger. Keratophyr). There are also nepheline-syenite-porphyry and nepheline-porphyry (with *tinguaite*), which are rocks of restricted distribution.

Of the rocks characterized by soda-lime-felspars, the types most nearly approaching the plutonic have been styled *diorite-porphyrite*, *etc.*, the others being termed simply porphyrites. Since some ferro-magnesian mineral is usually a prominent constituent, we have the divisions *mica-porphyrite*, *hornblende-porphyrite*, and *augite-porphyrite*. If a little porphyritic quartz be present, we have a *quartz-porphyrite* (quartz-mica-porphyrite).

It must be noted that writers who make no distinction in nomenclature between hypabyssal and volcanic rock-types use some of the above names in a more extended sense. Thus the Continental petrologists include under the term porphyrite the 'older' andesitic lavas, while some British authors apply the same name to andesites modified by secondary changes (partial decomposition, *etc.*). Some of the altered rocks styled propylites belong to the division now to be considered, others being lavas.

Constituent minerals. The *orthoclase* phenocrysts of the porphyries are similar to those of the quartz-porphyries and other acid intrusives. In the porphyrites this mineral does not occur except in the ground-mass. A *plagioclase* felspar accompanies the porphyritic orthoclase in many of the porphyries, and forms the most conspicuous phenocrysts in the porphyrites. Here it builds idiomorphic or rather rounded crystals, with twinning often on two or three different laws. It ranges in the porphyrites from oligoclase to labradorite, and frequently shows strong zoning between crossed nicols. A parallel intergrowth of orthoclase and plagioclase is common in some porphyries. In certain types of that family also occurs a felspar which has been referred to *anorthoclase*, while it has also been explained as a minute parallel intergrowth of

a potash- and a soda-lime-felspar. Viewed between crossed nicols, a crystal is often seen to be divided rather irregularly into portions with different optical behaviour, sometimes one part finely striated, another without visible striation. In certain special rocks (rhomb-porphyries) the crystal has a peculiar habit, which gives a lozenge-shaped section; in the ceratophyres it has the usual habit, giving rectangular sections.

As phenocrysts *quartz* is found only sparingly in a few rocks, but it enters into the ground-mass of all the more acid of the porphyries and porphyrites, though less abundantly than in the true acid rocks.

The most usual ferro-magnesian minerals are brown *biotite* and a pale or colourless idiomorphic *augite*. Some of the porphyrites have *hornblende* in sharply idiomorphic prisms, often twinned: it is more usually brown than green. In rocks rich in alkali the coloured constituent is often ægirine-augite or true *ægirine*.

As accessories, *apatite* and *iron-ores* (often titaniferous) may occur in varying quantity, the latter not being abundant. Exceptionally *olivine* and other minerals are present.

In the few rocks which contain *nepheline* that mineral occurs in one or two generations. As phenocrysts it is idiomorphic, while the little crystals in the ground-mass may or may not have definite shape. The 'liebenerite' pseudomorphs in certain porphyries have been supposed to represent nepheline. They consist essentially of a pale mica, and may with equal probability come from the destruction of cordierite. Some of these rocks rich in alkali carry melanite *garnet*.

Ground-mass and Structures. In the great majority of the rocks here considered the ground-mass is holocrystalline, with a fine texture and with various types of structure. It consists essentially of felspar or, in the more acid members, of felspar and quartz. In the porphyries the felspar is usually in minute prisms, short in comparison with their length, and as a rule untwinned. Quartz, if present, occurs interstitially. The little prisms may have more or less of a parallel arrangement, due to flow. Such short and

relatively stout prisms are usually referred to orthoclase: if the crystals have the 'lath'-shape, they are probably of a plagioclastic variety. Any approach to an allotriomorphic character is uncommon, and the micrographic intergrowths so frequent among the acid intrusives are not found here. In the nepheline-bearing rocks a more allotriomorphic type of structure is often found; while the bostonites and allied rocks show an approach to the volcanic trachytes, often with marked flow-structure.

The ground-mass of the porphyrites is also in general holocrystalline, consisting essentially of felspar, or, in the more acid varieties of felspar and quartz. In this latter case the rocks may reproduce some of the characteristic structures noted in the preceding chapter, such as the cyptocrystalline and the micrographic. Other porphyrites have the 'orthophyric' type of ground-mass (with short felspar-prisms), as in the porphyries, but there is every gradation from this to the allotriomorphic. In some of the more basic members the ground-mass consists of little lath-shaped plagioclase prisms with more or less noticeable flow-arrangement, an approach to the character of some andesites ('pilotaxitic' structure).

Glassy and vitrophyric rocks are not unknown in the families in question. Some of the Arran pitchstones, for example, have the composition of intermediate rather than acid rocks.

Leading types. Only a few illustrative examples will be selected, chiefly from British and American rocks.

Syenite-porphyries in considerable variety have been described from the United States. Some with hornblende occur in the Little Belt Mts, Mont.[1] From Cape Ann, Mass., Washington[2] describes dykes of quartz-syenite-porphyry, in which the coloured silicates are green hornblende and subordinate biotite. A rock from Coney Island, Salem, Mass., has abundant phenocrysts of felspar (microperthite and cryptoperthite) in a ground-mass of similar felspars and needles

[1] Pirsson, *20th Ann. Rep. U. S. Geol. Sur.* part III (1900) 513–515.
[2] *Journ. Geol.* (1899) vii, 108, 109.

of a greenish blue soda-amphibole (catophorite), with fluxion-structure. Augite-syenite-porphyry has been noted at Lake Chatauqua, N.Y., Albany, N.H. (with accessory bronzite), and other places. From the Sierra Nevada of California Turner[1] has described a 'soda-syenite-porphyry' resembling in some respects the Sölvsberg type; and a glaucophane-bearing rock of somewhat similar characters is found at Cape Ann, Mass.[2]

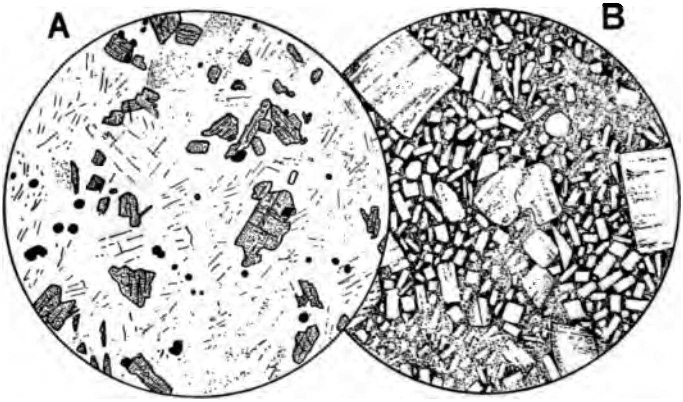

FIG 33. ORTHOPHYRES, SCOTLAND; × 20.

A. North Berwick Law; with crystals of green augite [3502].

B. Middle Eildon Hill, near Melrose; with interstitial patches of deep blue, nearly opaque, riebeckite [4602].

Rocks which belong to the *orthophyre* type (including orthoclase-porphyry) have been described, sometimes under the name trachyte, from several British localities. Those which occur as intrusions of Carboniferous age in Haddingtonshire[3] are in general non-porphyritic. The ferro-magnesian

[1] *17th Ann. Rep. U. S. Geol. Sur.* (1896) 665, 666, pl. XLIII.

[2] Washington, *A. J. S.* (1898) vi, 176–179. See also *Journ. Geol.* (1899) vii, 114–119.

[3] Hatch, *Trans. Roy. Soc. Edin.* (1892) xxxvii, 123–125, pl. I, figs. 3, 4; II, fig. 1.

mineral is a green soda-bearing augite, and the felspar which makes the bulk of the rocks must also be rich in soda. Such are the occurrences at North Berwick Law (Fig. 33, *A*) and the Bass Rock. In the Traprain Law rock Dr Hatch detected a little interstitial nepheline. In an example from Middle Eildon Hill, Melrose[1], the coloured silicate is a deep blue riebeckite, which occurs in little patches between the felspar crystals (Fig. 33, *B*). A few orthophyres, besides rocks with more trachytic structure, are found among the Tertiary dykes of the Skye region[2]. They carry sometimes biotite, sometimes hornblende. As a rock composed wholly of soda-felspars, an albite-porphyry has been recorded from Beinn Bràghaid in Sutherland[3], containing albite phenocrysts in a ground-mass essentially of the same mineral, with no other constituent.

Among the Devonian intrusions of the Christiania district occur the singùlar rocks known as *rhomb-porphyry* (Ger. Rhombenporphyr, Fig. 36, *A*). The phenocrysts of potash-soda-felspar, with their unusual crystallographic development, have been alluded to above. The crystals are often rounded and corroded, and they contain numerous inclusions of materials like the ground-mass. Some of the rocks contain pseudomorphs after olivine. The holocrystalline ground-mass consists of short prisms of felspar (probably orthoclase) with little granules of augite. Apatite is often plentiful, and grains of titaniferous iron-ore occur. In the same district there are lavas of like characters, though with finer texture, and these are common as boulders in the Eastern Counties of England.

The typical *bostonites* occur at Marblehead Neck near Boston, Mass.[4], in the Adirondacks[5], near Montreal, at Livermore Falls and Shackford, N.H., in the Apache Mts, Tex.,

[1] Barron, *G. M.* 1896, 376.

[2] *Tert. Ign. Rocks Skye* (1904) 287–289.

[3] Heddle, *M. M.* (1884) v, 141.

[4] Wadsworth, *Proc. Bost. Soc. Nat. Hist.* (1881) xxi, 290 ; Sears, *Bull. Mus. Comp. Zool.* (1890) xvi, 169–171 ; Washington, *Journ. Geol.* (1899) vii, 293.

[5] Kemp and Marsters, *Trans. N. Y. Acad. Sci.* (1891) xi, 14–16 ; *Bull. No.* 107 *U. S. Geol. Sur.* (1893) 18–22.

etc., as dykes in connection with nepheline-syenite or other plutonic rocks, and especially in intimate association with dykes of lamprophyre (camptonite). The bostonites consist essentially of felspar, quartz being never abundant and the ferro-magnesian silicates typically absent. Phenocrysts may or may not be developed, the bulk of the rock being a ground-mass of little felspar rods, often with partial flow-disposition and recalling the structure of the trachytes (Fig. 34, *A*). In

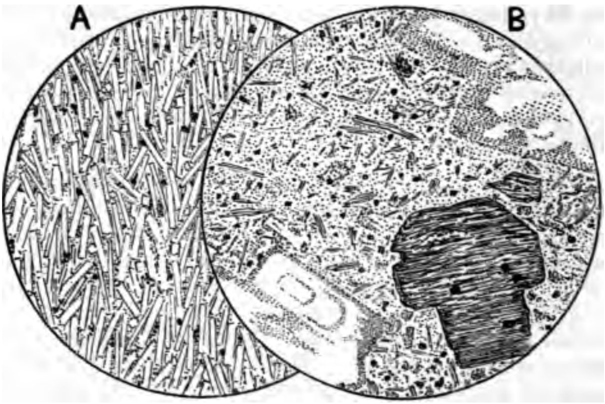

FIG. 34; × 20.

A. Bostonite, Marblehead Neck, Massachusetts; consisting essentially of little crystals of felspar (anorthoclase) with fluxional arrangement [2464].

B. Mica-porphyrite, Colvend, near Dalbeattie, Kirkcudbrightshire; with phenocrysts of zoned plagioclase and decaying biotite [2594].

many examples a high percentage of soda, with little or no plagioclase evident, points to a soda-orthoclase or anorthoclase, and indicates an affinity with the ceratophyres. Rocks approaching bostonite in character occur in the Limerick district[1] and in the western part of Sutherland; and an allied rock is described by Dr Flett[2] as forming a dyke at Onston

[1] Watts, *Guide*, 93.
[2] *Tr. Roy. Soc. Edin.* (1900) xxxix, 872, 873, pl. I, figs. 1, 2.

Ness in the Orkneys. This rock carries felspar phenocrysts: the ground-mass has the trachytic structure towards the margins of the dykes, but is allotriomorphic in the central part. The bostonite type is represented among the British Tertiary intrusions near Broadford and Elgol, in Skye[1].

The monzonites, like the syenites proper, have their porphyritic equivalents, characterized by the association of orthoclase and a soda-lime felspar as chief constituent minerals. A remarkable quartz-*monzonite-porphyry* occurs at Cushendun in Antrim. It contains abundant crystals of oligoclase, each bordered by a fringe of microperthite. The rest is of quartz and felspar, chiefly orthoclase, with small idiomorphic crystals of hornblende. Rocks which may be grouped as monzonite-porphyries have been recorded in the western states of America; *e.g.* a hornblende-bearing type forming sheets and dykes in the Rico Mts, Colorado[2].

Rosenbusch has given the name *tinguaite* to certain 'dyke-rocks' which have the composition of the (plutonic) nepheline-syenites and the (volcanic) phonolites, with structural characters which place them between those two families. Such rocks are associated with nepheline-syenites in Massachusetts (Essex Co.), Arkansas[3] (Fig. 35, *A*), and Texas (Apache Mts). Phenocrysts of orthoclase, often with marked tabular habit and with the characters of sanidine, are embedded in a fine-textured holocrystalline ground-mass of orthoclase with nepheline, ægirine, *etc.* This ground is typically allotriomorphic: when the little felspars take on the lath-shape with fluxional arrangement, the rocks do not differ essentially from phonolites. There may be phenocrysts of nepheline, and in one type (leucite-tinguaite) large pseudomorphs of orthoclase and nepheline occur in the form of leucite. This latter type, with pseudomorphs up to 6 inches in diameter, is found at Beemerville in New Jersey[4], and in Arkansas (Magnet Cove)[5] and Montana[6]. A variety remarkably rich in nepheline

[1] *Mem. Geol. Sur., Tert. Ign. Rocks Skye* (1904) 227, 289, 290.

[2] Cross, 21*st Annual Rep. U. S. Geol. Sur.*, part II (1900) 83–85.

[3] J. F. Williams, *Igneous Rocks of Arkansas*, vol. ii of *Ann. Rep. Geol. Sur. Ark.* for 1890, 100–106.

[4] Wolff, *Bull. Mus. Comp. Zool. Harvard* (1902) xxxviii, 273–277.

[5] J. F. Williams, *l.c.* 277–286.

[6] Pirsson, *A. J. S.* (1895) l, 394–398; *Bull.* 237 *U. S. Geol. Sur.* (1905) 126–130.

is found at Magnet Cove[1] and at Beemerville[2]. It has phenocrysts of nepheline up to an inch in diameter in a tinguaitic ground-mass composed chiefly of nepheline, charged with ægirine-needles, with some orthoclase, *etc*. A tinguaitic rock at Pickard's Point, Mass.[3], contains analcime and nepheline as the main elements of its ground-mass, and this analcime is considered to be a primary mineral[4]. Here may be mentioned also a remarkable dyke-rock (Heron Bay type) from the Lake Superior region, consisting to the extent of about one-half of analcime, in which are embedded orthoclase, labradorite, and ægirine[5].

Very beautiful tinguaites occur at Kosciusko, New South Wales[6] (see Fig. 35, *C*); and a porphyritic variety, with marked flow structure comes from Port Cygnet, Tasmania (Fig. 35, *B*); while Marshall[7] has described several tinguaite dykes from the Dunedin district of New Zealand.

Resembling the tinguaites in structure and general characters is the Sölvsberget type, described by Brögger in Southern Norway. In this, however, nepheline is wanting, and a certain amount of quartz may occur, the rocks thus graduating into the Grorud type, already mentioned (p. 121). Such a rock was described (under the name 'acmite-trachyte') by Wolff and Tarr[8] from the Crazy Mts in Montana. The phenocrysts are of anorthoclase and augite (bordered by ægirine) with occasional sodalite, and the ground-mass is of lath-shaped felspars (chiefly anorthoclase) and needles of ægirine, with a variable amount of nepheline and secondary analcime. Rocks more or less comparable with this occur

1 J. F. Williams, *l.c.* 259–261.

2 Kemp, *Trans. N. Y. Acad. Sci.* (1892) xi, 66, 67. This type is the 'sussexite' of Brögger, constituting the most basic member of a 'rock-series' of which the other members are grorudite, sölvsbergite, and tinguaite.

3 Sears, *Bull. Essex Inst.* (1893) xxv.

4 Washington, *A. J. S.* (1898) vi, 182–186.

5 Coleman, *Rep. Bur. Mines Toronto* (1899) viii, part II, 172, 173.

6 David and Guthrie, *Pr. Roy. Soc. N. S. W.* (1901) xxxv, 347–382. For other tinguaites see Card and Harper, *Rec. Geol. Sur. N. S. W.* (1905) viii, 36–42.

7 *Q. J. G. S.* (1906) lxii, 394–397, pl. XXXVII, fig. 2, XXXVIII, fig. 1.

8 *Bull. Mus. Comp. Zool. Harv.* (1893) xvi, 227–230: see also Pirsson, *Bull.* 237 *U. S. Geol. Sur.* (1905) 121–126 (Highwood Mts).

near Manchester in Massachusetts[1] and in the Apache Mts of Texas. Other occurrences have been recorded by Twelvetrees and Petterd at Port Cygnet in Tasmania, and by Prof. Gregory[2] at Mt Macedon in Victoria. In the latter case the characteristic ægirine is accompanied by riebeckite and cossyrite.

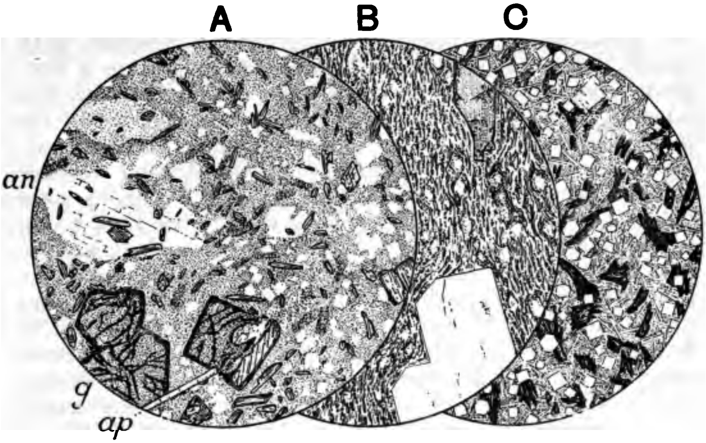

FIG. 35. TINGUAITES; × 20.

A. Hot Springs, Arkansas. The constituents are green ægirine-augite, nepheline, turbid felspar, and interstitial patches of clear analcime (*an*): as accessories brown melanite garnet (*g*) and apatite (*ap*) [4415].

B. Port Cygnet, Tasmania: showing phenocrysts of sanidine and ægirine-augite in a fluxional ground-mass of nepheline, ægirine-augite, and sanidine [4560].

C. Kosciusko, New South Wales: composed of nepheline, ægirine, and slender sanidine crystals, with some interstitial glass [4299].

Coming now to rocks of dioritic affinities, we find in the Western States of America abundant examples of *diorite-porphyrites*, more especially of the relatively acid types which

[1] Eakle, *A. J. S.* (1898) vi, 489–492; Washington, *Journ. Geol.* (1899) vii, 119, 120.

[2] *Tr. Roy. Soc. Vict.* (1902) xiv, 198, 199.

correspond with the quartz-diorites in the plutonic division. Iddings has described a quartz-mica-diorite-porphyrite, approaching granite-porphyry, from Electric Peak in the Yellowstone Park[1]. This has abundant small phenocrysts of felspars, quartz, and biotite, with a little hornblende, and a granular ground-mass of felspar and quartz. In the same district occur porphyrites, generally *hornblende-porphyrites*[2], carrying abundant phenocrysts of lime-soda-felspar and hornblende, with usually biotite and occasionally uralitized augite, in a fine-grained ground-mass. When the latter is rich in quartz, this mineral tends to form micropœcilitic patches enclosing the little felspar-prisms; when quartz is scarce, the felspars, which are, at least in the main, plagioclase, tend to have a felted arrangement. The ground-mass also contains some hornblende and biotite. Resembling the Electric Peak rocks, and like them of somewhat acid character as a whole, are the hornblende-porphyrites and hornblende-mica-porphyrites described by Cross[3] from the laccolites and associated intrusions of the Henry and Abajo Mts in Utah, the West Elk and El Late Mts in Colorado, *etc.* Among the phenocrysts the dominant minerals after plagioclase felspar (oligoclase or andesine) are hornblende and to a less extent biotite, while augite and hypersthene occur only locally. Quartz is also developed porphyritically and in certain cases large crystals of orthoclase, which, however, seem to belong rather to the same stage of consolidation as the ground-mass (Mt Carbon and Gothic Mt, in the West Elk group, *etc.*). The ground-mass is essentially an aggregate of orthoclase and quartz. Rocks generally resembling the above are described from the Sweet Grass Hills[4] and the Judith Mts[5], in Montana. The American 'propylites,' as defined by Zirkel, seem to belong to this place. A somewhat acid variety, with phenocrysts of quartz as well as oligoclase, comes from Shasta Co., California[6]. Prof. Sollas[7] describes somewhat similar rocks occurring as dykes of Palæozoic age in

[1] Iddings, 12*th Ann. Rep. U. S. Geol. Sur.* (1892) 617, 618.
[2] *Ibid.* 588–594.
[3] 14*th Ann. Rep. U. S. Geol. Sur.* (1891).
[4] Weed and Pirsson, *A. J. S.* (1895) l, 311.
[5] Pirsson, 18*th Ann. Rep. U. S. Geol. Sur.* part III (1898) 562–564.
[6] Iddings, in Diller, 233–236.
[7] *Rocks of Cape Colville Peninsula*, vol. i (1905).

the North Island of New Zealand, and constituting connecting links between quartz-diorite and dacite. The conversion of the hornblende to epidote is characteristic.

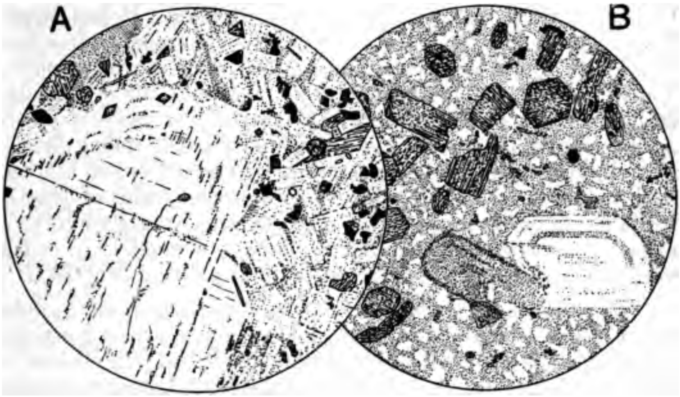

FIG. 36; × 20.

A. Rhomb-porphyry, dyke, Trosterud, near Christiania: showing a large phenocryst of cryptoperthite, with inclusions, in an orthophyric ground-mass of orthoclase, augite, magnetite, and some apatite and sphene [5182].

B. Hornblende-Porphyrite (Diorite-porphyrite), sill, N. of Loch Assynt, Sutherland: showing phenocrysts of hornblende and plagioclase in a felspathic ground-mass with some quartz [1681].

Various rocks of the porphyrite family are known in the British Isles, and especially in Scotland. Numerous *mica-porphyrite* dykes, of Old Red Sandstone age, occur in the Cheviots[1]. The felspar phenocrysts (oligoclase-andesine) are frequently rounded, and show carlsbad and albite twinning. The biotite-flakes are often bent, and sometimes show a resorption border. A colourless augite may also occur, and magnetite and apatite are minor constituents. The ground-mass is microcrystalline, fine-textured, and often obscured by decomposition. Quartz plays a variable part in it, and

[1] Watts, *Mem. Geol. Sur. Eng. and Wales, Expl. Sh.* 110 *S.W.* (1895) 62, 63; Kynaston, *Tr. Edin. G. S.* (1899) vii, 398–402.

there are some transitions to granophyre and quartz-porphyry. Indeed the mica-porphyrites in general often carry a notable amount of quartz in their ground-mass. The handsome rock which forms large intrusive sills in the Torridon Sandstone of Cansip, Sutherland, may also be placed here. It has large, frequently broken, phenocrysts of albite-oligoclase, and orthoclase also occurs, sometimes intergrown with the plagioclase. The dominant coloured mineral is biotite. The dykes described by Dr Teall[1] in Kirkcudbrightshire are mostly *mica-hornblende-porphyrites.* The phenocrysts are of zoned plagioclase in large individuals, green hornblende and brown biotite, both in good crystals, and sometimes corroded grains of quartz, while the fine-textured ground-mass contains quartz and orthoclase in addition to the other minerals named. In some varieties the hornblende is almost or quite wanting (Fig. 34, *B*).

Of *hornblende-porphyrites* we may recognize more than one variety. Some of the Scottish examples are of tonalitic rather than dioritic affinities (Cowal district of Argyllshire[2]). Again, there are the rocks which form sills of Lower Palæozoic age in the Assynt district of Sutherland[3] (Fig. 36, *B*). Here the hornblende is green and in very perfect crystals, often twinned: they sometimes show zonary colouring, and are occasionally hollow. A colourless augite in imperfect crystals sometimes accompanies the hornblende. The plagioclase phenocrysts show strong zonary banding between crossed nicols. Magnetite and apatite are present sparingly. The microcrystalline ground-mass is of felspar with subordinate quartz. These rocks are part of a variable set of intrusions. On the one hand is a non-porphyritic and coarser-textured type with allotriomorphic felspar (diorite), on the other a type with more abundant hornblende in two generations and with a 'panidiomorphic' ground-mass, which falls into the lamprophyre family (Spessart type; see p. 156). A hornblende-porphyrite of basic composition is seen in the Mawddach valley, near Dolgelly. It contains large and rather irregularly bounded twin-crystals of brown hornblende in a much de-

[1] *Mem. Geol. Sur. Scot., Expl. Sh.* 5 (1896) 44, 45, and *Silur. Rocks Scot.* (1899) 626, 627.
[2] Teall, *Mem. Geol. Sur. Scot., Geol. of Cowal* (1897) 103.
[3] Teall, *G. M.* 1886, 346–350.

composed matrix. Mr Phillips[1] termed this hornblende uralite, but there is no evidence that it is other than an original mineral. Hornblende-porphyrites occur also at Rhobell Fawr and in the Arenig district[2], where the hornblende crystals, with good outlines, are mostly replaced by epidote and other secondary products.

The rocks to which the name *augite-porphyrite* has been applied by German petrologists seem to be for the most part old augitic lavas, though intrusive types are also included. Such rocks, probably of Triassic age, are represented in the Monzoni district in the southern Tirol. Augite is, however, a frequent accessory mineral in the hornblende-porphyrites, and in particular occurrences may become the dominant coloured element of the rock. Thus in the Henry Mts Cross remarks augite-porphyrites at Mount Pennel and Mount Hillers; but these are mainly from sheets, while the great laccolites themselves are of the hornblendic type.

[1] *Q. J. G. S.* (1877) xxxiii, 427–429, pl. XIX.
[2] Fearnsides, *Q. J. G. S.* (1905) lxi, 632.

CHAPTER IX.

DOLERITES.

THE larger intrusive bodies of hypabyssal pyroxenic rocks, whether intermediate or basic in composition, have petrographical features which characterize them as a group with considerable individuality. It is to these rocks that we shall apply the name dolerite. Like their plutonic equivalents, the gabbros, they are holocrystalline and typically non-porphyritic, but they differ from the normal gabbros in their less coarse texture, in the absence of diallagic and other 'schiller' structures, and often also in the mutual relations of the felspar and augite which are their two chief constituents. In these respects there are, however, transitions between the two sets of rocks.

The dolerites occur as large dykes, sills, and laccolitic or other masses. Smaller intrusions of rocks having a similar chemical composition commonly have more of the petrographical characters of volcanic rocks. For these we shall retain the names andesite, basalt, *etc.*, and they will be excluded from this place.

In former editions of this book the name 'diabase' was used for this family of rocks. This term, however, is open to objection, since it has been, and still is, employed in different senses. By the German school it is restricted to the older rocks, whether hypabyssal or volcanic, dolerite and basalt being terms reserved for rocks of Tertiary or later age. Mr Allport[1] showed very conclusively that such a distinction

[1] *Q. J. G. S.* (1874) xxx, 565, 566.

corresponds with no real difference between the older and the newer rocks, and he abandoned the name diabase in favour of dolerite for all. The rocks so designated by Allport include some of the hypabyssal and others of the volcanic type. English writers have followed him in admitting no criterion of geological age into their classification and nomenclature, but some of them have inconveniently employed the name diabase for a more or less decomposed dolerite.

According to the absence or presence of the basic silicate olivine, the rocks of the present family are often divided into *dolerites* and *olivine-dolerites*. Olivine is in general found in the more basic members of the family, but this division does not correspond very exactly with the chemical division into intermediate (or sub-basic) and basic. By the presence of some other special mineral we may distinguish such types as *quartz-dolerite, hypersthene-dolerite, analcime-dolerite,* and *hornblende-dolerite.*

Various other names have been used for particular types of these rocks. Among the hornblende-bearing doleritic rocks of the Fichtelgebirge von Gümbel distinguished two types; proterobase, containing original hornblende in addition to augite, and epidiorite, in which the hornblende is all derived from augite. Some writers have extended these names to cover all dolerites characterized by primary and secondary hornblende respectively[1]. The old field-term 'greenstone,' referring to the staining of the rocks by chloritic and other decomposition-products, included not only dolerites but diorites, picrites, altered basalts, *etc.*, and so had no precise signification.

Constituent Minerals. The *felspars* of the dolerites range from oligoclase to anorthite in different examples: varieties of labradorite are perhaps the most common. The crystals have a strong tendency to idiomorphism, with columnar or sometimes tabular habit. Twin-lamellation on the albite law is universal, and is often combined with carlsbad twinning, but the pericline law is not so common. Zonary

[1] It is probable, however, that secondary hornblende has often been mistaken for primary.

growth is not often shown. Primary inclusions are not common, except glass-cavities and needles of apatite. Decomposition gives rise to calcite-dust, to finely divided material, which may be mica, to zeolites, or to granular epidote. The crystals also become charged with strings and patches of green chloritic substances, probably derived in part from the pyroxene.

The common pyroxenic constituent is an *augite,* usually without crystal outlines. It varies in thin slices from brown to nearly colourless, and rarely shows sensible pleochroism. Zonary and 'hour-glass' structures are sometimes seen. The orthopinacoidal twin is common, and in some cases there is a fine basal lamination[1] in addition (Whin Sill). The commonest decomposition-products are pale green, fibrous or scaly aggregates of serpentinous and chloritic substances. The former may be recognized by their low refractive index and moderately high birefringence; the latter are usually very feebly birefringent or sensibly isotropic, and show distinct pleochroism. Another change to which augite is subject is that which results in a light-green 'uralitic' hornblende. This is usually, but not always, fibrous in structure.

Some dolerites contain *bronzite* in addition to augite. It is in more or less idiomorphic crystals, with faint pleochroism, and gives rise by alteration to pseudomorphs of light green fibrous bastite. Only occasionally does *hornblende* appear as an original constituent. It seems to be characteristically a brown variety. Brown *biotite* is also a rare accessory.

A little *quartz* is found in some of the less basic dolerites, occurring interstitially. Whether it is original or a decomposition-product is sometimes difficult to decide, but when the mineral forms part of a micrographic intergrowth with felspar its primary nature may safely be assumed.

The *olivine,* which occurs in very many dolerites, builds more or less rounded idiomorphic crystals or grains, sensibly colourless or very pale. It has the same mode of alteration as in the olivine-gabbros and peridotites.

[1] Teall, *Q. J. G. S.* (1884) xl, pl. xxix, fig. 1.

The iron-ores, which, in contrast with some gabbros, the dolerites contain abundantly, include *ilmenite* and *magnetite*. The two are very commonly associated, and some so-called titaniferous magnetite has been supposed to be a minute intergrowth of the two[1]. They are easily distinguished when they occur as crystals or skeleton-crystals. In most cases the ilmenite has given rise to more or less of its characteristic decomposition-product, grey cloudy masses of semiopaque leucoxene[2] (fig. 37).

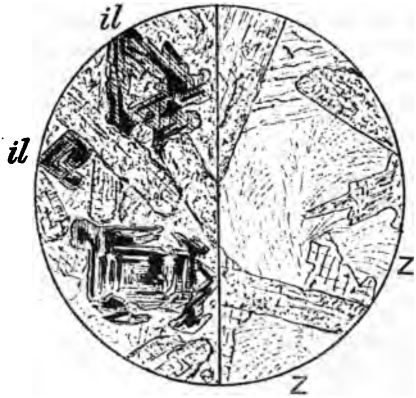

FIG. 37. DECOMPOSING DOLERITE, DENEIO, NEAR PWLLHELI, CAERNARVONSHIRE; × 20.

This shows decomposing felspar-crystals and ophitic augite, with ilmenite-skeletons (*il*), crusted with leucoxene, and patches of radiating fibres of a zeolitic mineral (*z*) [123].

Long columnar or needle-like crystals of *apatite* occur in most dolerites, and sometimes in abundance (fig. 38, *B*), but they are often capriciously distributed.

Structure. As regards structure, the dolerites offer a contrast to most plutonic rocks, owing mainly to the fact that the crystallization of the felspar has preceded that of the

[1] Teall, *Q. J. G. S.* (1884) xl, 650, 651, pl. XXIX, figs. 4–7.
[2] Cohen (3), pl. LXI, fig. 4; Teall, pl. XVII, fig. 2.

dominant ferro-magnesian constituent. As seen in a slice, the columnar crystals of felspar show more or less elongated sections, with no law of arrangement, and around or between these the augite is moulded. The last-named mineral in most cases distinctly wraps round the felspar crystals, and often forms plates of some extent, enclosing many of them. This is known as the *ophitic* structure (figs. 38, *A*, 39, *A*). In other cases the augite tends to form more or less rounded grains embedded in a plexus of lath-shaped felspars, adjacent grains not being parts of one crystal but showing different orientations (fig. 38, *B*). This is what Prof. Judd[1] has styled the *granulitic* structure: he considers it due to movement towards the end of the process of consolidation. In both types, if olivine is present it is always idiomorphic towards the augite,

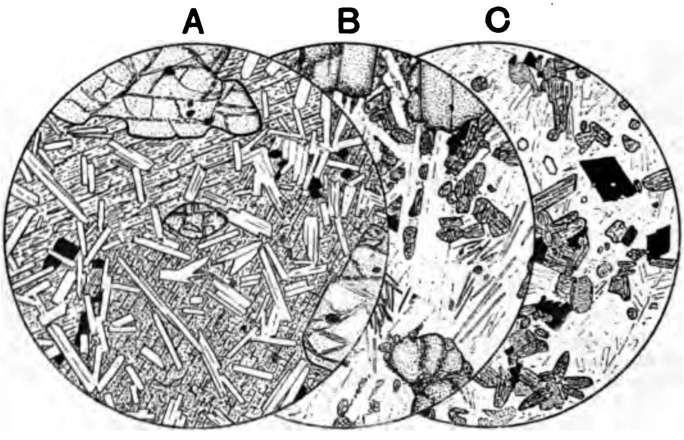

FIG. 38. STRUCTURES OF OLIVINE-DOLERITES; × 20.

A. Tobermory, Mull: with typical ophitic structure [1105].

B. Muckraw, Linlithgow: augite granulitic, with tendency to idiomorphism; abundant needles of apatite [118].

C. Rowley Regis, near Birmingham: augite in idiomorphic crystals [4119].

[1] *Q. J. G. S.* (1886) xlii, pp. 68, 76, and figs. pl. v.

but may be penetrated by the felspar prisms (fig. 39, *A*). Only quite exceptionally does the augite have idiomorphic shape (fig. 38, *C*). The rhombic pyroxene is constantly of earlier crystallization than the augite, and may show good outlines. The iron-ores are often idiomorphic, but magnetite may be in part later than the felspar.

A porphyritic character, due to the development of relatively large crystals of felspar at an early stage, is not common: it is sometimes connected with an increasing fineness of texture of the rock on approaching the edge of an intrusive mass. Other occasional marginal peculiarities are flow-phenomena, vesicles or amygdules, and the development of a glassy base or sometimes of variolitic and allied structures.

Leading types. A true *quartz-dolerite* (*i.e.* with primary quartz) is a somewhat unusual type. A good example is the Great Whin Sill[1], which is intrusive in Lower Carboniferous strata, and extends from the Northumberland coast to the Eden valley. In its coarser central parts it sometimes approaches a gabbro in aspect and the augite becomes idiomorphic; the fine-textured portions near the margin, on the other hand, take on an andesitic character, developing perhaps some glassy base; but the bulk of the intrusion is of dolerite of a distinctive type. The normal structure is more or less ophitic, and the dominant constituents are a lath-shaped felspar, near andesine, and a pale brown augite, often with basal striation. The iron-ore is titaniferous, and may perhaps represent minute intergrowths of magnetite and ilmenite. An accessory mineral is bronzite, tending to be replaced in the usual fashion; brown mica is occasionally seen, and a little brown hornblende is often present, bordering the augite with crystallographic relation. Quartz is detected in all the coarser varieties of the rock, and is at least in part original, since it frequently occurs in micrographic intergrowth with felspar. Similar rocks are known from Ratho, near Edinburgh[2], and from Dura Den, in Fife[3]. With these rocks we may also compare that near Stirling[4]. The general mass of this is a simple dolerite, the

[1] Teall, *Q. J. G. S.* (1884) xl, 640–657, pl. xxix: also *Brit. Petr.* pl. xiii, fig. 2.

[2] Teall, p. 190.

[3] Flett, *Mem. Geol. Sur. Scot., Geol. E. Fife* (1902) 391.

[4] Monckton, *Q. J. G. S.* (1895) li, 480–491.

augite often showing basal striation, but there are coarse-textured veins, which contain quartz in delicate micrographic intergrowth with part of the felspar.

Some of the numerous dolerite dykes which traverse the old gneiss of Sutherland are quartz-bearing (Loch Glencoul, *etc.*). The chief constituent minerals are a basic plagioclase and a pale or colourless augite, the relations between the two being rather variable. A green or yellow-green hornblende occurs as a marginal alteration of the augite, especially around the grains of magnetite, and a little brown biotite is also associated with the latter. The hornblende is connected with mechanical stress in the rock, and specimens may be collected to show the complete amphibolization of the augite.

The Penmaenmawr[1] intrusion, in North Wales, is also characterized by quartz occurring interstitially in a micrographic intergrowth. In this rock bronzite becomes an essential constituent, being quite as abundant as the pale brown augite. The latter mineral often shows the delicate basal striation already noticed. Biotite is sometimes rather abundant. The structure of the rock is rather granulitic than ophitic, and it usually shows some approach to the characters of volcanic rocks in the occurrence of more than one generation of felspar. Some of the latest shapeless crystals are to be referred to orthoclase. The rock passes into a type which would be properly described as an andesite. The general body of the rock is traversed by comparatively coarse segregation-veins of more acid composition[2].

Quartz-dolerites are not unknown in America; *e.g.*, at Newhaven[3] and Medford, Conn., in the Province of Quebec, and near St John, N.B.[4]

The numerous sills of Ordovician age in Caernarvonshire[5] are of *dolerite without olivine*, and have almost universally the ophitic structure. The felspar gives lath-shaped or rectangular sections from ·05 to ·5 inch long, with albite- but only occasionally pericline-lamellation: it often has extinction-

[1] *Bala Volc. Ser. Caern.* (1889) 65; Teall, pl. xxxv, fig. 2.
[2] Waller, *Midland Naturalist* (1885) viii, 1–7.
[3] Pirsson, in Diller, 264–273.
[4] Matthew, *Trans. N. Y. Acad. Sci.* (1895) xiv, 213, 214, pl. xv, fig. 2.
[5] *Bala. Volc. Ser. Caern.* (1889) 75–86.

angles indicating labradorite and neighbouring varieties. The augite is pale brown to almost colourless, and very rarely shows any approach to idiomorphism. Besides the commoner decomposition-products, there is often a fibrous colourless hornblende, fringing the augite but occupying the place of destroyed felspar, *etc.* The iron ores include both magnetite and ilmenite, often together, and apatite is locally plentiful. Rhombic pyroxene is wanting, as well as olivine, while original hornblende and quartz are practically absent, and biotite very exceptional. These Caernarvonshire rocks are thus of very simple mineralogical constitution. Despite the absence of olivine, they are of thoroughly basic composition. The dolerites of similar age in Wicklow are also free from olivine, and are probably of more acid composition, some of them containing quartz. They are characterized by a partial or even total conversion of the ophitic augite into hornblende, with other changes ascribed to dynamic metamorphism[1].

In the intrusions of the Fishguard district, Pembrokeshire, Mr Reed[2] found the felspar to be an oligoclase-andesine. Some of the rocks in this district contain a rhombic pyroxene. From the Breidden Hills, in Montgomeryshire, again, Prof. Watts[3] has described altered ophitic dolerites, in which a rhombic pyroxene, as represented by serpentinous pseudomorphs, is sometimes more plentiful than the augite. Such rocks may be styled *hypersthene dolerites*. Dolerites carrying hypersthene or bronzite in addition to augite occur in the Shelve district of Shropshire, in the neighbourhood of Tremadoc, and about Arenig Fawr. In these last Mr Fearnsides[4] proved the felspar to be andesine, and such rocks are clearly assignable to the less basic section of the dolerite family, corresponding with pyroxene-andesites rather than with basalts in the volcanic division. In these Arenig intrusions the habit of the augite may be ophitic or subophitic or partly idiomorphic. Ilmenite, with leucoxenic alteration, is a noticeable constituent.

[1] Hatch, *G. M.* (1889) 263–265.
[2] *Q. J. G. S.* (1895) li, 180–193: see also Elsden, *ibid.* (1905) lxi, 581-584.
[3] *Ibid.* (1885) xli, 544.
[4] *Ibid.* (1905) lxi, 630, 631.

Dykes of dolerite free from olivine are frequent in the older rocks of the North-West Highlands of Scotland[1]. They are composed of felspar, pale augite with a subophitic habit, and titaniferous iron-ore. There is often a green hornblende in addition, but Dr Teall has shown that this is formed at the expense of the augite as an effect of dynamic metamorphism.

Numerous *olivine-dolerites* are associated with the Carboniferous strata of the Midlands. Good examples are seen in the Clee Hills, Shropshire[2]. The rock of Pouk Hill[3], near Walsall, is an ophitic variety. In that of Rowley, near Birmingham, the augite occurs in little grains, and tends to be idiomorphic[4] (fig. 38, *C*), or again there is a micrographic intergrowth of augite and felspar[5]. In this rock are relatively acid segregation-veins, in which part of the felspar is orthoclase[6]. Ophitic olivine-dolerites occur again in Derbyshire[7], and in some of these Mr Arnold-Bemrose[8] has described certain peculiar pseudomorphs after olivine.

Numerous intrusions of olivine-dolerite, with prevalent ophitic structure, occur in the Carboniferous strata of the Edinburgh district[9], Fife[10], and other parts of Scotland. Some of these rocks, probably of Carboniferous age, are considerably affected by decomposition, the felspars giving rise to zeolites, the ilmenite to leucoxene, *etc.*

A great group of olivine-dolerite sills is found in the Inner Hebrides and in Antrim, intruded mostly among the Tertiary basalts[11]. These rocks consist of olivine, felspar

[1] Teall, *Q. J. G. S.* (1885) xli, 135, 146; *Brit. Petr.* pl. XIX, fig. 1 (Scourie, Sutherland).

[2] This and many other British examples were noticed by Allport, *Q. J. G. S.* (1874) xxx, 529–567.

[3] Watts, *Pr. Geol. Ass.* (1898) xv, 397–400.

[4] Teall, pl. XI.

[5] *Ibid.* pl. XXIII, fig. 2.

[6] Waller, *Midl. Natst.* (1885) viii, 261–266.

[7] Teall, pl. IX; Arnold-Bemrose, *Q. J. G. S.* (1899) lv, pl. XX, figs. 1–3.

[8] *Q. J. G. S.* (1895) li, 613–616, pl. XXIV.

[9] Cole's *Stud. Micro. Sci.* (1882) No. 32 (Corstorphine Hill).

[10] Flett, *Mem. Geol. Sur. Scot., Geol. E. Fife*, 390–393.

[11] *Mem. Geol. Sur., Tert. Ign. Rocks Skye* (1904) 247–250; Teall, pl. x.

(usually a basic labradorite), pale brown augite, magnetite, and a little apatite. The structure is, as a rule, typically ophitic (figs. 38, *A*, 39, *A* and *B*). A porphyritic variety is found on Roineval and elsewhere in Skye[1] and more abundantly in Canna. This encloses crystals of labradorite up to an inch in length. In a more remarkable rock from some localities in Skye[2], Eigg, *etc.* (Mugeary type) the felspar, which makes up about 70 per cent. of the whole, is principally oligoclase, with some orthoclase. The other chief constituents are magnetite, olivine, and augite, the last in varying amount and sometimes wanting. Apatite is unusually abundant. The rocks are typically of fine texture.

The basic dykes of the British Tertiary igneous region[3] exhibit much more variety than the sills. The ophitic type

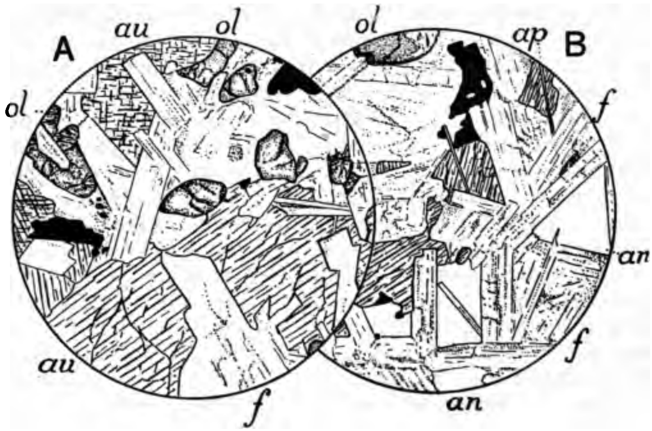

FIG. 39. BRITISH TERTIARY OLIVINE-DOLERITES ; × 20.

A. Fair Head, Antrim: showing typical ophitic structure on rather a coarse scale. Note that the olivine is in part moulded on the felspar [3642].

B. Dippin, Arran: with interstitial patches of clear primary analcime (*an*) [3128].

[1] *Mem. Geol. Sur., Tert. Ign. Rocks Skye* (1904) 262–264.
[2] *Ibid.* 264–266.
[3] *Ibid.* 320–331, pl. XXII, figs. 2, 4, 5, and XXV, fig. 1.

of olivine-dolerite is common, but rocks devoid of olivine are also frequent, and there is considerable variety of micro-structure. The porphyritic character is much more often met with in the dykes than in the sills. Some dykes probably of this age occur outside the generally recognized area of Tertiary igneous activity, *e.g.* on the Menai Straits. These are for the most part without olivine, and some of them are andesitic rather than basaltic dolerites, while the smaller ones have rather the character of augite-andesites.

Without entering into an account of particular occurrences in America, it may be stated that dykes of dolerite, and especially of olivine-dolerite, are widely distributed in the Archæan and other ancient formations of Canada and the north-eastern United States[1].

An interesting type, though not of wide distribution, is *analcime-dolerite.* The mineral named is, of course, well known as an alteration-product from the soda-bearing felspars and nepheline, but it seems to be sufficiently established that it may also occur as a primary igneous mineral. Examples occur in Shropshire (Clee Hills) and in Arran (Clauchland Hills and Dippin[2], see fig. 39, *B*), where patches of clear analcime are present interstitially in ophitic dolerites. It is found only in the fresh rocks, and in more altered examples is replaced by radiating fibres of other zeolites (natrolite, *etc.*). An ophitic dolerite with analcime, regarded by Mr Young[3] as secondary after felspar, occurs at Gullane Hill; but in other cases in the Edinburgh district it is at least possible that the mineral is of primary origin. Here too, at Car Craig, Dr Teall[4] has described a rock differing in structure from the ophitic dolerites and richer in analcime. It has a purplish brown, pleochroic augite, and contains altered felspar, analcime and other zeolites, iron ores, and brown mica (probably secondary). It presents points in common with the neighbouring picrite of Inchcolm. A somewhat similar rock is found at Spalefield,

[1] A list of references to described examples is given by Kemp and Marsters, *Bull. No.* 107 *U. S. Geol. Sur.* (1893) 28, 29.

[2] *Mem. Geol. Sur. Scot., Geol. N. Arran* (1903) 112–114.

[3] *Tr. Edin. Geol. Soc.* (1905) viii, 326–335.

[4] *Brit. Petr.* 191, pl. XXII, fig. 1.

near Anstruther, in Fife[1], and other examples come from Bathgate in Linlithgowshire[2]. These rocks agree well with the *teschenites* of Hohenegger, from Silesia and Moravia. With them may be compared certain examples from San Luis Obispo Co., California[3], in which the structure varies from the ophitic to the 'panidiomorphic.' A teschenite occurs also near Montreal[4], and good examples have been described from Wellington Province, New Zealand[5]. The teschenites, especially if the analcime is derived in part or wholly from nepheline, have evident affinities with the theralites.

[1] Flett, *Mem. Geol. Sur. Scot., Geol. E. Fife* (1902) 392, 393.
[2] *Summary of Progress Geol. Sur.* for 1905, 74, 75.
[3] Fairbanks, *Bull. Dep. Geol. Univ. Calif.* (1895) i, 273–300, plate.
[4] Harrington, *Can. Nat.* ix, 245; *Rep. Geol. Sur. Can.* for 1877–8, 429.
[5] Sollas in *Rocks of C. Colville Peninsula*, vol. ii (1906) 155-157, with plates.

CHAPTER X.

LAMPROPHYRES.

THE lamprophyres are a peculiar group of rocks occurring typically as dykes or other small intrusions. Chemically they are characterized by containing, with a medium or low silica-percentage, a considerable relative quantity of alkalies (especially potash), while the oxides of the diatomic elements are also abundantly represented. This shows itself in the commoner types of lamprophyres by an abundance of brown mica, and indeed the lamprophyres as a family are rich in ferro-magnesian silicates. They are fine-grained rocks, but almost always holocrystalline, and their structure is in some respects peculiar.

Von Gümbel's name lamprophyre has been extended by Rosenbusch to cover the various members of this family. The best known varieties are mica-lamprophyres ('mica-traps,' Ger. Glimmertrapp). Of these, two types have long been recognized, a chief point of distinction being the predominance of orthoclase in one and plagioclase in the other. To these types are given the names, respectively, *minette* (a word taken from the miners of the Vosges) and *kersantite* (from Kersanton, near Brest). To these Rosenbusch added two other types for rocks in which the place of biotite is taken by augite or hornblende. He separated those with dominant orthoclase (*vogesite*) from those with dominant plagioclase (*camptonite*). It should be noted that the criterion of the felspars does not lead in this family to a very natural division, especially when much of the potash in the rocks is present in mica. Other

types (spessartite, odinite, *etc.*) have since been separated; but for most purposes it is perhaps sufficient to distinguish the rocks merely as mica-, hornblende-, and augite-lamprophyres. There are other types of very basic composition, which are devoid of felspar, including the *monchiquites*, characterized by analcime, and the *alnöites*, containing melilite as an important constituent. These are of rare occurrence.

Constituent minerals. The characteristic mineral of those lamprophyres most usually met with is *biotite*, which occurs in hexagonal flakes. The extinction-angle (3° or 4°) is sufficient to show frequently a lamellar twinning parallel to the basal cleavage. The flakes are very commonly bleached in the interior, retaining only at the margin the normal deep brown colour (fig. 40, *A*). With the bleaching there is a certain diminution in birefringence. More rarely we find a dark interior with a pale border, or a dark nucleus and border with a pale intermediate zone. Complete decomposition results in a pale, feebly polarizing substance as a pseudomorph. A greenish chloritic alteration is also found. Iron-oxide separates out, usually as limonite, and other minerals are produced as little wedges or lenticles along the cleavages of the mica (fig. 40, *A*). The titanic acid of the mica separates out as rutile, in fine needles arranged in three sets at angles of 60°: this is well seen in basal sections. The original inclusions of the biotite are apatite, and sometimes magnetite and zircon.

Short columnar crystals of *augite* occur in many lamprophyres, showing sharp outlines with an octagonal cross-section, and sometimes lamellar twinning. When fresh, the mineral is pale green or almost colourless in slices, but it is readily replaced by serpentine, calcite, chlorite, *etc.*, in good pseudomorphs (fig. 40, *C*). In other cases uralitization may be noticed. The augite crystals are sometimes coated with flakes of biotite. The most usual occurrence of *hornblende* is in long well-shaped prisms, frequently twinned, but it has some variety of habit. The colour is brown or sometimes green. The mineral may be converted into a chloritic substance with separation of iron-oxides.

A striking feature in the lamprophyres is that the felspars do not usually occur as phenocrysts. The nature of the felspar

in the more altered rocks can be verified only after removing the carbonates from the slice with dilute acid. The small columnar or tabular crystals of *plagioclase* show albite-lamellation and frequently zonary banding. They often have a kind of sheaf-like grouping. Decomposition, beginning in the interior, gives rise to abundant calcite. The *orthoclase*, and perhaps anorthoclase, build short rectangular crystals, simple or carlsbad twins, often clouded or with ferruginous staining. The monchiquites have no felspar, but some at least contain *analcime*, always interstitial; while *melilite* is the characteristic mineral of the alnöites.

Some of the more acid lamprophyres have a certain amount of *quartz*, which is either the latest product of consolidation or is intergrown with a portion of the felspar with micrographic structure.

A common accessory in some lamprophyres, and an essential in certain types, is *olivine*, which builds relatively large perfect crystals, or sometimes groups of rounded grains. It is occasionally found fresh, but very commonly represented by pseudomorphs of carbonates and serpentine (fig. 40, *B*).

The iron-ores are not often very abundant, and may be quite wanting. The most usual is *pyrites*, but octahedra of *magnetite* are also found.

A constant and abundant accessory is *apatite*, but it is sometimes in such fine needles as to be invisible except by oblique illumination. Sphene and zircon are only exceptionally met with.

Structures and peculiarities. Many of the lamprophyres are non-porphyritic, with a rather exceptional structure due to a strong tendency to idiomorphism of all the constituent minerals. This is the 'panidiomorphic' structure of Rosenbusch[1]. The porphyritic members of the family, again, have a peculiarity, in that the porphyritic character is produced by a recurrence of the ferro-magnesian constituents, not of the felspars. Any recurrence of the latter, and especially of orthoclase, is rare, but two generations of biotite or of horn-

[1] See chromolithograph of kersantite in Berwerth, *Lief.* I; and of augite-minette in *Lief.* III.

blende are seen in many of the rocks. When olivine occurs, it is in conspicuous crystals, but only of one generation.

Without showing any real flow-structure, the felspars of the rock sometimes have a special grouping in sheaf-like or rudely radiating fashion. Exceptionally orthoclase is moulded on the other constituents: usually it is idiomorphic, save when it builds micrographic structures with quartz. There is little indication of any isotropic residue in the typical lamprophyres, though in some cases little ovoid vesicles, filled with secondary products, suggest the former presence of some glassy matter, now perhaps devitrified. In some of the monchiquites, however, there is what has been described as a glassy base. The mica-lamprophyres are remarkably prone to decomposition, and often have 20 or 30 per cent. of calcite and other secondary products.

Grains of quartz and crystals of alkali-felspars are found, though very sparingly, in many lamprophyres. Their sporadic occurrence and, still more, some curious features which they invariably present compel us to regard them as something apart from the normal constitution of the rock and of quasi-foreign origin. The *enclosed quartz grains* are of rounded form, with evident signs of corrosion, and are seen to be surrounded by a narrow ring or shell due to a reaction between the quartz and the surrounding magma. This shell is probably in the first place of augite, but it is often found to consist of minute flakes of greenish fibrous hornblende or of calcite and chloritic products. The quartz having this mode of occurrence must be distinguished from genuine derived fragments torn from other rocks: these are of irregular form, often complex, and may contain inclusions unknown in the corroded quartz-grains.

The *enclosed felspar crystals* are always of an acid species—either orthoclase or a plagioclase rich in soda. The crystals are corroded so as to present a rounded outline, but not reduced to mere round grains. The plagioclase thus corroded is bordered by a narrow margin of orthoclase due to the action of the magma.

Illustrative examples. The best-known British examples occur as small dykes and sills in the north of England[1],

[1] *G. M.* 1892, 199–206, with numerous references.

and are of an age between the Silurian and the Carboniferous. The dykes are numerous in the southern part of the Lake District, from Windermere to Shap and on to Sedbergh, and they are seen again in the Lower Palæozoic inliers of Ingleton, Edenside, and Teesdale. The rocks are *mica-lamprophyres*, but many of them contain subordinate augite, always in perfect crystals, but often decomposed. The relative proportions of orthoclase and plagioclase vary, so that some examples would be named minette and others kersantite, the latter being perhaps the commoner. Good pseudomorphs after olivine are seen in the dykes in the Sedbergh district (fig. 40, *B*). The dykes at Cronkley, in Teesdale, have abundant pseudomorphs with hexagonal and quadrangular outlines representing some mineral not yet certainly identified.

Scattered quartz-grains with the characteristic corrosion-border occur in many of the dykes[1]; and felspars, both ortho-

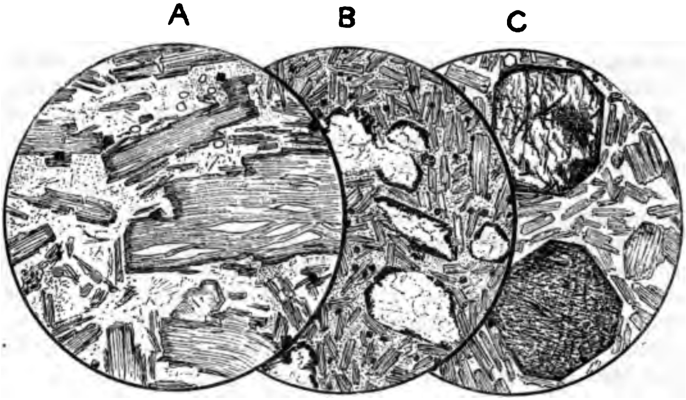

FIG. 40. BRITISH MICA-LAMPROPHYRES ; ×18.

A. Helm Gill, near Dent, Yorkshire. The mica-flakes show each a dark border and a bleached interior. There are also lenticles of secondary products intercalated along the cleavage-planes [444].

B. Rawthey Bridge, near Sedbergh, Yorkshire. Olivine has been present in abundance, and is now replaced by some rhombohedral carbonate with a border of iron-oxide [2728].

C. St Heliers, Jersey. Showing octagonal cross-sections of augite, largely replaced by secondary products [1094].

[1] Adye's *Stud. Micropetr.* pl. VI, fig. 1.

clase and oligoclase, are enclosed sporadically in the Edenside intrusions, and more abundantly in those to the south of the Shap granite. These rocks show various transitions from typical lamprophyres to a micaceous quartz-porphyry of one of the less acid types, and indeed very different kinds of rocks occur imperfectly mingled in one and the same dyke.

Quartz does not occur as a normal constituent in most of the north-country lamprophyres, though it is found in the transitional rocks just mentioned. In an intrusion at Sale Fell, near Bassenthwaite[1], quartz occurs partly as interstitial grains, partly in micrographic intergrowth, and the rock shows considerable resemblance to the original kersantites of Brittany.

Mica-lamprophyres are known also from the Isle of Man (Peel Castle), Galloway[2], the Cowal district of Argyllshire, Invernessshire (Farley near Beauly[3]), and some parts of Ireland.

An augite-bearing minette seems to be one of the commonest types of lamprophyres. It is seen in Cornwall (Trelissick Creek, *etc.*), in the Channel Islands (Doyle Monument, Guernsey; St Heliers, Jersey, fig. 40, *C*), *etc.*

In America mica-lamprophyres of the minette type have been described from Coanicut Island, R.I.[4], Franklin Furnace, N.J.[5], Nôtre Dame Bay in Newfoundland[6] (with accessory augite and hornblende), and the Sweet Grass Hills[7] (with augite) and Little Belt Mountains[8], Mont. The kersantite type is recorded from the Sierra Nevada region of California (Mariposa, Hamilton, *etc.*), and an augite-vogesite from the Black Hills of Dakota[9].

More than one type of *hornblende-lamprophyre* is found in the British Isles. Vogesites, consisting essentially of idiomorphic hornblende and orthoclase felspar, occur in the

[1] 20*th Cent. Atlas*, 34, with plate.
[2] Teall, *Mem. Geol. Sur., Silur. Rocks Scot.* (1899) 628, 629.
[3] Horne, *M. M.* (1886) vii, p. iv.
[4] Pirsson, *A. J. S.* (1893) xlvi, 374.
[5] Iddings, in Diller, 236–239.
[6] Wadsworth, *A. J. S.* (1884) xxviii, 99, 100.
[7] Weed and Pirsson, *A. J. S.* (1895) l, 313.
[8] Pirsson, 20*th Ann. Rep. U. S. G. S.*, part III (1900) 526–531, pl. LXXVI, *A*.
[9] J. D. Irving, *Ann. N. Y. Acad. Sci.* (1899) xii, 287.

western part of Sutherland (fig. 41, *A*). Other occurrences have been described as camptonites; but Dr Flett[1] has pointed out that most of these belong rather to the less basic Spessart type, allied to vogesite. Such rocks are found in the neighbourhood of Beinn Nevis (Sgòr Chalum, *etc.*[2]), and rocks more or less closely allied occur in Galloway (Black Gairy Hill[3]) and in the Cowal district of Argyllshire[4]. Some lamprophyre sills and dykes in the Assynt district of Sutherland[5] also belong here. They have abundant slender, twinned crystals of green hornblende, sometimes of hollow shape. In Ireland hornblendic, as well as micaceous, lamprophyres are known from Galway, the

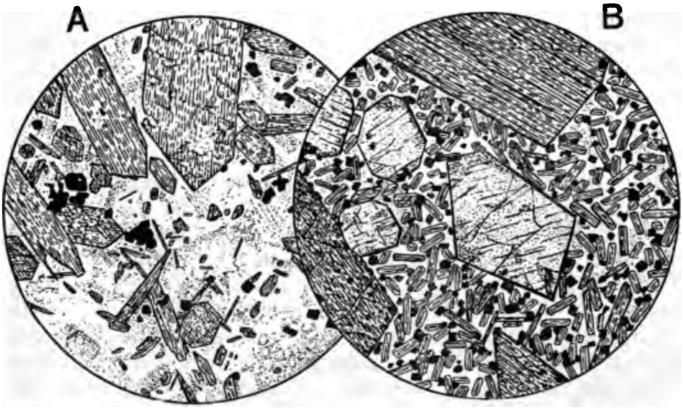

FIG. 41. HORNBLENDE-LAMPROPHYRES; ×20.

A. Vogesite, Loyne Bridge, Assynt, Sutherland: composed of green hornblende and orthoclase, with a little plagioclase and magnetite [3261].

B. Camptonite, Mæna, near Gran, Norway. A porphyritic type, with conspicuous crystals of brown hornblende and colourless augite in a ground-mass of brown hornblende, abundant magnetite, and plagioclase felspar [4612].

1 *Summary of Progress Geol. Sur.* for 1901, 69.
2 Teall, *Summary of Progress Geol. Sur.* for 1898, 48.
3 Teall, *Mem. Geol. Sur., Silur. Rocks Scot.* (1891) pl. xxv, fig. 2.
4 Teall, *Mem. Geol. Sur. Scot., Geol. Cowal* (1897) 116–118.
5 Teall, *G. M.* 1886, 346–353.

Raphoe district, the coast of Down, *etc.* Prof. Watts[1] describes one from Lettery, near Clifden, as a camptonite, another from Clondermot, near Raphoe, as a vogesite, and most of those in Co. Down carry hornblende in addition to biotite. Hyland[2] noted camptonites from the east shore of Lough Swilly and vogesites from other localities in Donegal, and another camptonite has been recorded from Convoy in the same county[3]. In England some of the Warwickshire rocks originally described as diorites are camptonites, particularly one from Marston Jabet[4]. This contains abundant brown hornblende in idiomorphic elongated crystals. Some of these rocks carry porphyritic augite, and some contain olivine.

In the north-eastern United States and in Canada hornblende-lamprophyres of the camptonite type are widely distributed. The name was first applied by Rosenbusch to rocks described by Hawes[5] from Campton Falls, N.H., while closely similar rocks are found near Montreal[6], at Summit Station[7] and Mount Ascutney[8], Vt., at several points on the Hudson River highlands[9] and in the Lake Champlain district[10], and (with less abundant hornblende) at the Forest of Dean iron-mine, N.Y.[11] In all these idiomorphic brown hornblende, usually in two generations, is the chief constituent, felspar is subordinate, and augite is at most an accessory. In other varieties augite becomes prominent in addition to the dominant hornblende : a feature found also in other districts (fig. 41, *B*). Both vogesites and camptonites are recognized in the Sierra Nevada[12].

[1] *Guide*, 53, 73–75.
[2] *Mem. Geol. Sur., Geol. of Innishowen* (1890) 44, 45.
[3] Cole and Cunningham, *Sci. Pr. Roy. Dubl. Soc.* (1900) ix (N.S.), 318–320, pl. XIX, fig. 2.
[4] Allport, *Q. J. G. S.* (1879) xxv, 638, 639 ; Watts, *Pr. Geol. Ass.* (1898) xv, 394 ; Teall, pl. XXIX, fig. 2.
[5] *A. J. S.* (1879) xvii, 147–151 : also Iddings, in Diller, 239, 240 ; and see Berwerth, *Lief.* II.
[6] Harrington, *Rep. Geol. Sur. Can.* 1878 ; *Can. Natst.* ix, 243, 244.
[7] Nason, *A. J. S.* (1889) xxxviii, 229.
[8] Jaggar, *Bull.* 148 *U. S. G. S.* (1897) 70.
[9] Kemp, *Amer. Naturalist*, 1888, 694–696, pl. XII.
[10] Kemp and Marsters, *Trans. N. Y. Acad. Sci.* (1891) xi, 21, 22 ; *Bull. No.* 107 *U. S. Geol. Sur.* (1893) 29–32.
[11] Kemp, *A. J. S.* (1888) xxxv, 331, 332.
[12] Lawson, *Bull. Dep. Geol. Univ. Calif.* (1904) iii, 372–374 (Upper Kern Basin).

Hornblendic and augitic lamprophyres, carrying plagioclase and orthoclase, are found at Cambewarra Mt, N.S.W.[1] In New Zealand camptonites, including some with augite as the chief porphyritic element, occur in the Westland district[2]. By the phenocrysts losing their sharply idiomorphic outline, and by the coming in of porphyritic felspars, these rocks graduate into hornblende- and augite-porphyrites.

In this place we may most conveniently notice the monchiquites and limburgites, although these rocks occur as lava-flows as well as small intrusive masses. The prominent constituents are usually olivine and augite. The olivine is of a variety rich in iron, and often becomes converted at the margin to red hæmatite or brown limonite. The augite is frequently of a pale violet-brown colour, with strong zonary structure; and there may be a second generation of smaller crystals. These minerals, with magnetite and apatite, are embedded in a generally isotropic base, which is either of a strong brown tint or quite colourless. The brown base is of glass, and this may be taken as the distinctive character of the *limburgites* proper[3]. In the allied 'augitite' olivine is wanting, and augite is the only important mineral. The colourless isotropic base found in many rocks which have otherwise the general characters of the limburgites has been shown in numerous instances to be analcime[4], and this is probably the case in general, although some difference of opinion exists on this point. Such rocks may be termed *monchiquites*, and the corresponding type devoid of olivine is sometimes distinguished under the name fourchite. Other varieties arise from the substitution of hornblende or biotite for augite (fig. 42, *A*). The name *analcime-basalt* has sometimes been used for monchiquitic rocks with indubitable analcime, but may be more conveniently restricted to those transitional varieties in which a certain amount of felspar is present in addition, usually confined to the ground-mass. It may be remarked,

[1] Card and Jaquet, *Rec. Geol. Sur. N. S. W.* (1903) vii, 119–131, pl. XXVII, figs. 1, 2, 4.

[2] Bell, *The Geology of the Hokitika Sheet, Bull.* 1 (*N.S.*) *N. Z. Geol. Sur.* (1906) pp. 82, 83.

[3] On the original limburgite of the Kaiserstuhl, Baden, see Bonney, *G. M.* 1901, 411–417.

[4] Pirsson, *Journ. of Geol.* (1896) iv, 679–690; Evans, *Q. J. G. S.* (1901) lvii, 38–53; Card, *loc. cit. sub.*

however, that the felspar seems to be usually orthoclase or an acid plagioclase.

Monchiquites occur among the Carboniferous intrusions of Scotland. A rock of this kind from Chester's quarry, Whitelaw, near Haddington, was described by Dr Hatch[1] under the name limburgite. It is in a very fresh condition. There are abundant well-shaped phenocrysts of olivine and augite, the latter having a very pale violet-brown tint in the interior, deepening towards the margin, with slight pleochroism. These minerals, with imperfect crystals of magnetite, occur in a ground-mass consisting of small augite-prisms set in a colourless base, which is chiefly of analcime, though, as in some other rocks of this type, there is sometimes a little birefringent matter, which may be nepheline or felspar. Similar rocks are found at other localities in Haddingtonshire and Fife (*e.g.* Chapel Ness, near Elie), and they have been recorded by Prof. Watts in Ireland[2]. Analcime-basalts, *i.e.* monchiquitic rocks with a noteworthy amount of felspar, also occur in the Scottish area (*e.g.* Mathers, Haddington). In the Orkneys Dr Flett[3] has described dykes of monchiquite, including a hornblendic variety, and of a hornblende-fourchite. He considers the colourless base to be originally glassy.

In the United States monchiquites are known in the Lake Champlain district[4], Montana[5], Colorado[6], and Arkansas[7]. The non-peridotic type, fourchite, is also found in some of these areas[8]; and there is the rarer Ouachita type[9], also

[1] *Trans. Roy. Soc. Edin.* (1892) xxxvii, 116, 117, pl. I, fig. 1; *cf.* *20th Cent. Atlas*, 41, with plate.

[2] *Rep. Brit. Assoc.* for 1892, 727 (Nicker Hill, Limerick); *Guide*, 38, 94 (Phillipstown, Queen's Co.).

[3] *Trans. Roy. Soc. Edin.* (1900) xxxix, 887–896, with plates.

[4] Kemp and Marsters, *Trans. N. Y. Acad. Sci.* (1891) ix, 22, 23; *Bull. No.* 107 *U. S. Geol. Sur.* (1893) 32–35.

[5] Lindgren, *Proc. Calif. Acad. Sci.* (1890) iii, 51 (Highwood Mts); Weed and Pirsson, *Bull No.* 139 *U. S. G. S.* (1896) 114–117 (Castle Mt); Pirsson, *20th Ann. Rep. U. S. G. S.* part III (1900) 543–550 (Little Belt Mts).

[6] Cross, *Journ. of Geol.* (1897) v, 684–693; Graton, *Prof. Paper* 54; *U. S. G. S.* (1906) 95, 96, pl. IX, fig. *B*.

[7] J. F. Williams, *Ign. Rocks Ark.*, vol. ii of *Rep. Geol. Sur. Ark.* for 1890, 151–157, 290–295, 353.

[8] J. F. Williams, *l.c.* 107, 108, 290; Kemp and Marsters, *l.c.* 35, 36.

[9] Kemp in *Ign. Rocks Ark.* 394–398.

devoid of olivine but very rich in biotite. In New South Wales dykes of analcime-basalt and allied varieties occur at Bondi and other places near Sydney[1].

The *alnöites*, originally described under the name melilite-basalt from Alnö, off the coast of Sweden, are defined by Rosenbusch as olivine-rich biotite-monchiquites with a variable content of melilite and perofskite. The only rocks of this kind known in Britain are those described by Dr Flett[2] from the Orkneys, where they form dykes cutting the Old Red Sandstone and associated with others of camptonite and monchiquite. One from Rennibuster, near Kirkwall, has for phenocrysts large irregular plates of biotite, small serpentinized olivines,

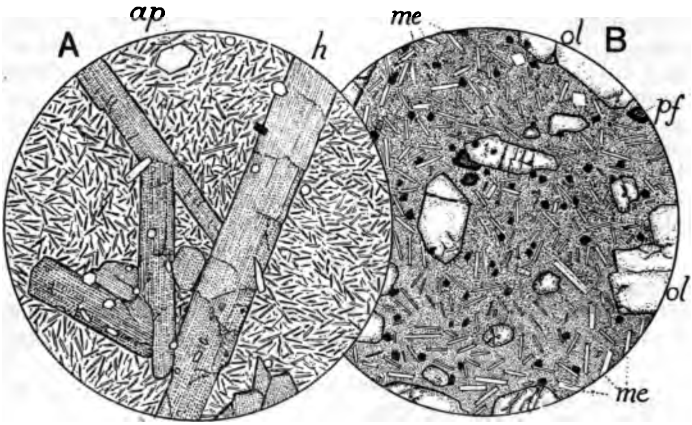

FIG. 42. ULTRABASIC LAMPROPHYRES; × 20.

A. Hornblende-Monchiquite or Fourchite, Fernando Noronha, Brazil: contains phenocrysts of apatite (*ap*) and brown hornblende (*h*), with a few of pale augite in other parts of the slide, in a ground-mass of clear analcime crowded with slender hornblende crystals [4724].

B. Alnöite, Spiegel River, Cape Colony. The constituents are deep brown perofskite (*pf*), magnetite, olivine (*ol*), flakes of melilite (*me*), granules of augite, and interstitial glass [3022].

[1] Curran, *Journ. Roy. Soc. N. S. W.* (1894) 217–231, with plates; Card, *Rec. Geol. Sur. N. S. W.* (1902) vii, 93–101, pl. XXVI; Card and Harper, *ibid.* (1905) viii, 43–56, pl. XI, *b*, figs. 1–3 (Kiama district).

[2] *Tr. Roy. Soc. Edin.* (1900) xxxix, 892–898, pl. III, figs. 4–6.

and some large idiomorphic crystals of augite. The ground-mass consists of abundant small augites of purplish-brown colour, idiomorphic melilite, and interstitial matter representing altered glass or perhaps nepheline. Another, from Naversdale near Orphir, has the melilite in allotriomorphic patches, showing peg-structure. The mineral is often replaced by zeolites, calcite, *etc.* An allied type is described under the name melilite-monchiquite. A good alnöite, of Silurian age, is found at Ste Anne de Bellevue, near Montreal[1]. Here the phenocrysts are brown mica in large and abundant crystals, olivine more or less converted to hæmatite, and augite: the ground-mass is of mica, olivine, augite, magnetite, and melilite, with apatite and perofskite, the last a mineral rarely absent from such rocks. The melilite is the latest product of consolidation, forming imperfect crystals of tabular habit with the characteristic 'peg-structure.' A rock from Mannheim, N.Y.[2], differs from this chiefly in the absence of pyroxene. A beautiful example (fig. 42, *B*) comes from Spiegel River, Cape Colony, and the type is represented at other localities in the South African diamond-fields[3]. Another rock of this type is found at Shannon Tier in Tasmania[4].

[1] Adams, *A. J. S.* (1892) xliii, 269–279.
[2] Smyth, *A. J. S.* (1893) xlvi, 104–107; (1896) ii, 290–292.
[3] Rogers, *Ann. Rep. C. G. H. Geol. Comm.* for 1898, 62; for 1903, 50, 51; Adye's *Stud. Micropetr.* 27, 28, pl. VI, fig. 2.
[4] Twelvetrees and Petterd, *Papers and Proc. R. S. Tas.* for 1898–9 (1900) 60–64.

C. VOLCANIC ROCKS.

UNDER this head we shall treat only the solid rocks of volcanic origin (lavas), reserving the fragmental products of volcanic action for the sedimentary group. With the true extruded lava-flows will be included similar rocks occurring in the form of dykes, *etc.*, in direct connection with volcanic centres, the common feature of all being that they have consolidated from fusion under superficial conditions, *i.e.* by comparatively rapid cooling under low pressure. This mode of origin has given the rocks as a whole characters which place them in contrast with the plutonic group, while the types treated above under the head of 'hypabyssal' have in some respects intermediate characters. Many volcanic outpourings have undoubtedly been submarine, and when these have taken place under a great depth of water the products may be expected to approximate in some measure to the characters of rocks of hypabyssal origin. In general, however, the contrast between volcanic and plutonic types of structure is well marked.

The presence of a glassy (or devitrified) residue, though not peculiar to volcanic rocks, is highly characteristic of them, and especially of the more acid types. Other features characteristic of lavas, though not confined to them, are the vesicular and amygdaloidal structures, and the various fluxion-phenomena, including flow-lines, parallel orientation of phenocrysts, banding, drawing out of vesicles, *etc.*

The great majority of the volcanic rocks have a porphyritic structure, and their constituents belong to two distinct periods of consolidation, the earlier represented by the porphyritic

crystals or 'phenocrysts,' and the later by the 'ground-mass,' which encloses them, and commonly makes up the bulk of the rock. This ground-mass may, and usually does, include some glassy residue or 'base': if the ground is wholly glassy, we have what is termed the 'vitrophyric' structure. The same mineral may occur both among the phenocrysts and as a constituent of the ground-mass. When such a recurrence is found, the crystals of the earlier generation are distinguished from those of the later by their larger size, often by their more perfect idiomorphism, and in some cases by fracture, corrosion, or other evidence of vicissitudes in their history. The two periods of consolidation are styled by Rosenbusch the 'intratelluric' and the 'effusive,' the former being considered as the result of crystallization prior to the pouring out of the lava, and so under more or less deep-seated conditions. When we speak of the consolidation of a lava at the earth's surface, we must be understood to refer to the ground-mass of the rock. In some few types of lavas the phenocrysts fail altogether, and the effusive period is the only one represented.

The various types will be grouped under families, to be taken roughly in order, beginning with the most acid. It is customary to speak of the several families of lavas as answering to the commonly recognized families of the plutonic rocks—the rhyolites to the granites, the trachytes to the syenites, *etc.*—but such a correspondence cannot be followed out with great exactness. It is certain that a given rock-magma may result in very different mineral-aggregates according as its consolidation is effected under deep-seated or under surface conditions; and in the latter case, moreover, much of the rock produced may consist of unindividualised glass.

It is more especially in the volcanic rocks that the Continental petrologists have insisted upon a division into an 'older' and a 'younger' series ('palæovolcanic' and 'neovolcanic'), an arbitrary line being drawn between the pre-Tertiary lavas and the Tertiary and Recent. This distinction is rejected by the British school, and will find no place in the following pages[1]. The simplified grouping of the volcanic

[1] On this question see *Sci. Progr.* (1894), ii, 48–63.

rocks by their essential characters, without reference to their age or supposed age, involves some modification of the double nomenclature in use among the German and French writers. The names employed by them for the younger lavas only will here be extended to all rocks of the same character, irrespective of their geological antiquity. The names applied by the Continental writers to the pre-Tertiary lavas have also been used habitually for hypabyssal rock-types, and may now be restricted to these latter. Some of them (quartz-porphyry, porphyrite, *etc.*) we have already used in this sense.

CHAPTER XI.

RHYOLITES.

In the rhyolite family we include all the truly acid lavas; rocks of porphyritic or vitrophyric structure, in which alkali-felspars and usually quartz figure as the chief constituent minerals. By the older writers most of these rocks were included, with others, under the large division 'trachyte.' The present family was separated by von Richthofen with the name 'rhyolite,' expressing the fact that flow-structures are commonly prominent in the rocks. Roth used the term 'liparite' in nearly the same sense. The Continental petrographers, following their regular principle, use these names for the Tertiary and Recent acid lavas only, the older (pre-Tertiary) being more or less arbitrarily separated and designated by other names (quartz-porphyry, porphyry, *etc.*); and some English geologists have tacitly adopted a like division, calling the older rhyolites, which have often suffered various secondary changes, quartz-felsites, felsites, *etc.*

Some petrologists distinguish between potash- and soda-rhyolites, according to the predominance of one or the other of the alkalies; but in fine-textured or glassy rocks this difference does not always express itself in the minerals evident. There is, however, a peculiar group of lavas rich in alkalies, especially in soda, the pantellerites of Förstner. The more acid of these may be attached to the rhyolite family.

We shall consider briefly the characters of the phenocrysts or enclosed crystals and of the ground-mass. In some rhyolites the phenocrysts occur only sparingly, or may even fail altogether.

Phenocrysts. Among the phenocrysts or porphyritically enclosed crystals of the rhyolites, the most constant are alkali-felspars; both *orthoclase* (including *sanidine*) in tabular or columnar crystals, simple or twinned, and an acid plagioclase, ranging from *albite* to *oligoclase*, in tabular crystals with the usual twin-lamellation. A parallel intergrowth of the mono-clinic and triclinic species is occasionally found. The felspars often contain glass-[1] and gas-cavities, but rarely fluid-pores: such minerals as apatite, magnetite, biotite, *etc.*, may be sparingly enclosed. Certain rocks specially rich in soda (pantellerites, *etc.*) have *anorthoclase*.

Quartz, when present, occurs in dihexahedral crystals, often corroded and with inlets of the ground-mass. Besides occasional inclusions of minerals of early consolidation, it contains glass- but rarely fluid-cavities.

The more basic silicates are not present in great abundance. The most usual is *biotite* in deep-brown hexagonal flakes, with only occasional inclusions of apatite, zircon, or magnetite. A greenish *augite* with octagonal cross-section may be present, but brown *hornblende* is much less common. The pantellerites have the brown triclinic amphibole *cossyrite*, with intense absorption and pleochroism.

The most usual iron-ore is *magnetite*, but it is rarely abundant. Needles of *apatite* and minute crystals of highly refringent and birefringent *zircon* may also occur in small quantity. In rarer cases *garnet* is found instead of a ferro-magnesian bisilicate.

Ground-mass and structures. The rhyolites exhibit in their ground-mass a great variety of texture and structure. The texture may be wholly or partly glassy; or cryptocrystalline, often with special structures; or, again, evidently crystalline, though on a minute scale. Further, these several varieties of ground-mass may be associated in the same rock and in the same microscopical specimen. Fluxion is frequently marked by banding, successive bands being of different textures, so that thin layers of glassy and stony or spherulitic nature alternate with one another.

[1] Cohen (3) pl. IX, fig. 4.

The *vitreous* type of ground-mass alone is found in the *obsidians*[1]. These rocks, colourless or very pale yellow in thin slices, afford good examples of structures common to all the natural glasses; especially the *perlitic cracks* (fig. 43) produced by contraction of the homogeneous material[2], and the *vesicular* structure due to the rock-magma having been distended by steam-bubbles. In extreme cases the cavities are so numerous as to make up the chief part of the volume of the rock, and we have the well-known pumice (Fr. ponce, Ger. Bimstein). The vesicles are commonly elongated in the direction of flow, and may even be drawn out into capillary tubes. In the older lavas vesicles are usually filled by secondary products, and become amygdales.

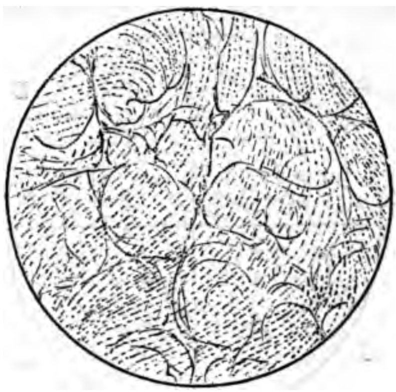

FIG. 43. GLASSY RHYOLITE (OBSIDIAN), TELKIBANYA, NEAR SCHEMNITZ, HUNGARY; × 20.

Showing sinuous flow-lines traversed by a system of curving perlitic fissures [G. 329].

[1] The less common glassy rocks of the trachyte and phonolite family and of the dacites are also termed obsidian. They are not easily distinguished from the rhyolite-glasses. Some of the rocks styled pitchstones are lavas of the obsidian type, usually of acid composition (*e.g.* the 'Meissen pitchstones,' in Saxony).

[2] Cohen (3), pl. LXXI, figs. 1, 2.

In many cases a ground-mass consisting essentially of glass encloses minute bodies known as *crystallites* (fig. 44), which may be regarded as embryonic crystals[1]. They have definite forms, but no perfect crystal boundaries, and the more rudimentary types cannot be subjected to optical tests to determine their nature. The simplest effort at individualisation from the vitreous mass results in globulites, minute spherical bodies without action on polarized light. They occur in profusion in many obsidians, either uniformly distributed or aggregated into cloudy patches (cumulites). From the partial coalescence of a series of globulites, arranged in a line, result margarites[2], resembling strings of pearls (fig. 44, *A*). A high-power objective (say $\frac{1}{8}$ inch) is often necessary to resolve this beaded structure. Long threads of this nature may extend in the direction of flow but with numerous little twists (fig. 44, *D*).

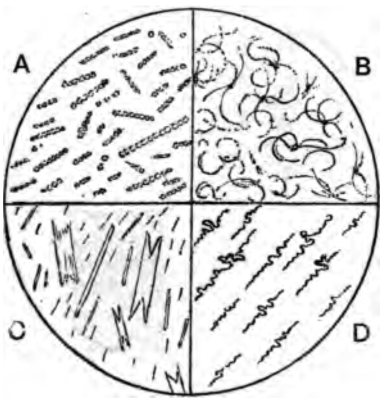

FIG. 44. CRYSTALLITES IN OBSIDIAN.

A. Margarites, Obsidian Cliff, Yellowstone Park; × 400 [477].
B. Trichites, Telkibanya, Hungary; × 100 [G. 327].
C. Longulites and swallow-tailed crystallites, Hlinik, Hungary; × 200 [G. 70].
D. Flow-structure marked by arrangement of twisted trichites, Prabacti, Java; × 200 [G. 64].

[1] See Rutley, *M. M.* (1891) ix, 261–271, and plate; Zirkel, *Micro. Petr. Fortieth Parallel*, pl. IX, figs. 1–4; Rosenbusch-Iddings, pl. II, III.
[2] Cohen (3), pl. VI.

Similar threads with curved hair-like form, known as trichites, often occur in groups originating in a common nucleus. These bodies, in which a beaded structure may or may not be observable, seem to belong to a stage of development later than the cessation of flowing movement in the mass (fig. 44, *B*). The small rod-like bodies known as longulites, sometimes slightly clubbed at the ends[1], may be regarded as built up by the complete union of rows of globulites. They occur in crowds, with a marked arrangement parallel to the direction of flow. The transition from margarites to longulites is often seen, some of the little rods resolving into beaded strings, while others do not. The larger crystallitic bodies termed microlites are possibly to be conceived as built up from longulites. Various incomplete stages may be observed, the ends of the imperfect microlites having a brush-like form (scopulites of Rutley) or being forked in swallow-tail fashion (fig. 44, *C*). Fully developed microlites have an elongated form, and are indeed small crystals giving the optical reactions proper to the mineral (felspar, augite, hornblende, *etc.*) of which they consist.

An original *cryptocrystalline* or 'microfelsitic' ground-mass is found in some rhyolites, though it seems to be more characteristic of intrusive types (approaching what we have styled quartz-porphyries) than of true surface lavas. It consists in a granular mixture of felspar and quartz on so minute a scale that the individual grains cannot be resolved in a thin slice. There is no doubt, however, that in many old acid lavas a cryptocrystalline ground-mass has resulted from the *devitrification* (Ger. Entglasung) of a rock originally vitreous. The process has often begun along perlitic fissures, or flow-lines, and the successive stages are beautifully displayed in such rocks as the Permian rhyolites ('pitchstones') of Meissen in Saxony. No single criterion can be set up for distinguishing an original from a secondary cryptocrystalline structure. In a rock otherwise fresh, however, there will generally be no reason to suspect devitrification; while, on the other hand, the presence of perlitic cracks is often taken to indicate that the rock in which they occur was originally glassy[2].

[1] Fouqué and Lévy, pl. xvi, fig. 2.

[2] Some American writers have used the name 'aporhyolite' for such devitrified rhyolites.

A *microcrystalline* (as distinguished from cryptocrystalline) ground-mass is not very prevalent in true acid lavas, but may occur as bands alternating with glassy or microspherulitic bands, often on a small scale. When an evident microcrystalline structure has been set up as a secondary alteration, it probably indicates, as a rule, something more than the merely physical change of devitrification. It is often connected with an introduction of silica from an external source, and in the resulting microcrystalline mosaic quartz often plays a more important part than it would do in a normal igneous rock. In some of the partly silicified Ordovician rhyolites of Westmorland a secondary quartz-mosaic still shows clear indication of former perlitic cracks, outlined by dust, as well as the characteristic banding. In these rocks, too, *silicification* has sometimes affected not only the ground-mass but the felspar phenocrysts.

Spherulitic and allied structures. The spherulitic growths which are common in many acid lavas may be conveniently divided into the larger and the smaller. Under the former head we have spherulites, often isolated, with diameters ranging from a fraction of an inch to several inches. They are best studied in certain obsidians, where they are usually of distinctly globular form and with well-defined boundary. The examples which have been most carefully examined, and may be taken as typical, consist mainly of extremely delicate fibres of felspar, arranged radially and on the whole straight, but often forked or branching[1]. In the spherulites of perfectly fresh rocks the space between the fibres is found to be occupied in great part by aggregates of tridymite. In older spherulites, where tridymite is not recognized, quartz may perhaps be considered to represent it. In any case the structure is to be made out only in carefully prepared and very thin slices. It may often be observed that the flow-lines of the lava pass undisturbed through the spherulites, indicating that the latter crystallized after the cessation of movement. Spherulites are

[1] See Cross, *Bull. Phil. Soc. Washington* (1891) xi, 411–414; Iddings, *ibid.* 445–464, with plates. Similar structures occur in dykes on Druim an Eidhne, near Loch Coruisk, Skye: see Judd, *Q. J. G. S.* (1893) xlix, pl. II, III; Harker, *Tertiary Igneous Rocks of Skye*, *Mem. Geol. Sur.* (1904) 283–286, pl. XI, XII, and XXII, fig. 3.

often developed along particular lines of flow, and may coalesce into bands (fig. 45).

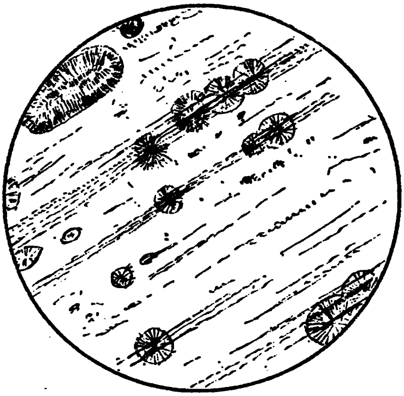

FIG. 45. OBSIDIAN, VULCANO, LIPARI IS.; × 20.

The glassy matrix encloses isolated spherulites with some tendency to coalesce in bands following the direction of flow. The flow-lines pass uninterruptedly through the spherulites [1785].

These larger spherulites show many special peculiarities in different examples. Sometimes their outward extension has been effected in two or more stages, which are marked by a change in the character of the growth. Again, curious phenomena arise from the formation of shrinkage-cavities (*lithophyses*) in connection with spherulites. Some remarkable examples of lithophyses have been described from the Yellowstone Park[1] and other districts in the United States[2], from Hungary, and from Lipari[3]. A peculiar feature is the occurrence in the hollows of perfect crystals of the iron-olivine (fayalite), as well as aggregates of tridymite, and in some cases crystals of garnet, topaz, *etc.* The complex forms of these

[1] Iddings, *Obsidian Cliff*, in *7th Ann. Rep. U. S. Geol. Surv.* (1888) 265, 266, pl. XII–XIV; *A. J. S.* (1887) xxxiii, 36–43.

[2] Nathrop, Colorado; see Cross, *Proc. Colo. Sci. Soc.* (1886) 62–66.

[3] Cole and Butler, *Q. J. G. S.* (1892) xlviii, 438–443, pl. XII; Johnston-Lavis, *G. M.* 1892, 488–491.

lithophyses can be realized only from specimens or figures. They must be distinguished from ordinary ovoid vesicles.

The large spherulites are in some cases only skeleton-structures, the divergent rays being embedded in glass. Such *skeleton-spherulites*, in a devitrified matrix, have been described by Prof. Cole[1] in the 'pyromérides' of Wuenheim, in the Vosges.

Examination of the older acid lavas shows that the large spherulites are specially susceptible to certain chemical changes. They are often found partly or totally replaced by flint or quartz, while their insoluble decomposition-products remain as roughly concentric shells of a chloritic or pinitoid substance. Again, a central hollow is often found, and it is not always clear whether this is due entirely to decomposition or partly represents an original lithophysal cavity[2], nodular structures originating in both ways being represented in many districts.

The very minute spherulites commonly occur in large numbers, closely packed together, so as to constitute the chief bulk of particular bands, or even of the whole ground-mass of the rock. This is the *microspherulitic* structure[3]. The true nature of these very minute bodies, as composed of fine fibres of felspar with quartz, is a matter rather inferred than seen in any given case; but the radiate growth is detected by means of the 'black cross,' which each individual spherulite shows between crossed nicols (figs. 46, *A*; 47, *C*). These minute spherulites seem to be much less readily destroyed than the larger ones. The *axiolites* of Zirkel[4] seem to be of the nature of elongated spherulites, the fibres radiating not from a point but from an axis (fig. 46, *A*); or they may be conceived as representing the coalescence of a row of minute spherulites (*cf.* fig. 45).

Any evident micrographic structure is not common in the ground-mass of rhyolites, though bands or streaks having this

[1] *G. M.* 1887, 299–303.

[2] See especially Cole, *Q. J. G. S.* (1886) xlii, 183–190; (1892) xlviii, 443–445; Parkinson, *ibid.* (1901) lvii, 211–225, pl. VIII.

[3] See Teall, pl. XXXVIII.

[4] *Micro. Petr. Fortieth Parallel*, pl. VI, fig. 2. But compare Cole, *M. M.* (1891) ix, 271–274.

character are sometimes found. A curious feature, first described by Iddings in some obsidians from the Yellowstone Park[1] and rhyolites from the Eureka district of Nevada[2], is the occurrence of porphyritic 'granophyre groups' or *micropegmatite phenocrysts* in a glassy, cryptocrystalline, or microcrystalline ground-mass (see fig. 46, *B*). In these the quartz is subordinate to the felspar in quantity, and the micrographic groups often show the crystal-boundaries of the latter mineral. As a rule, however, there are several felspar crystals grouped together, the whole permeated by wedges of quartz, and the outline is complex or rather irregular[3].

A structure met with in the ground of some rhyolites, and in certain bands of laminated rhyolites, differs essentially from

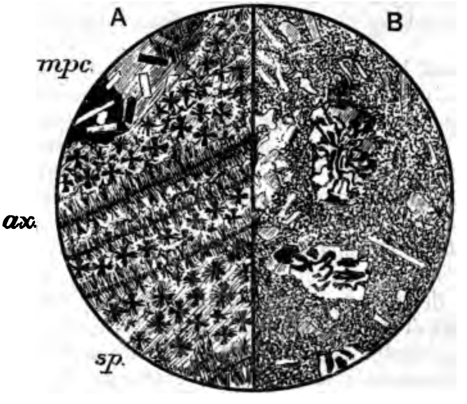

FIG. 46. SPECIAL STRUCTURES IN RHYOLITES, × 20; CROSSED NICOLS.

A. Falls of Gibbon River, Yellowstone Park: different bands, following the flow-lines, show micropœcilitic (*mpc*), axiolitic (*ax*), and microspherulitic (*sp*) structures [1430].

B. Goodwick, near Fishguard, Pembrokeshire; showing micropegmatite phenocrysts in a finely microcrystalline ground-mass [2289].

[1] *7th Ann. Rep. U. S. Geol. Sur.* (1888) 274–276, pl. xv.

[2] *Monog.* xx *G. S. Geol. Sur.* (1893) 375, pl. v, fig. 2.

[3] Compare *Tertiary Igneous Rocks of Skye*, *Mem. Geol. Sur.* (1904) 282, 284, 285, pl. xx, fig. 2, where similar peculiarities are described in rhyolitic dykes.

the micrographic, in that it indicates the successive, instead of simultaneous, crystallization of the two constituent minerals. Minute felspar crystals with no orderly arrangement are enclosed in little ovoid or irregular areas of quartz, the whole of the quartz in such a little area being in crystalline continuity. This structure reproduces on a minute scale the ophitic and pœcilitic structures presented by different minerals in other rocks, and Prof. G. H. Williams[1] adopted for it the term *micro-pœcilitic* (fig. 46, *A*).

An original holocrystalline texture on other than a minute scale is rarely, if ever, met with in true rhyolites. The 'nevadite' of Richthofen is exceptional in that the ground-mass is quite subordinate in quantity to the crowded phenocrysts, but this ground-mass is commonly glassy. In part, at least, these rocks belong to the dacites rather than the rhyolites.

Leading types. Fresh Tertiary rhyolites are not widely represented in the British Isles, but some good examples come from Antrim, and show a considerable range of micro-structure. The glassy type (obsidian) occurs at Sandy Braes, and contains phenocrysts of quartz, with less abundant felspar, in a ground-mass of glass enclosing numerous microlites of felspar (fig. 47, *A*). There is a pronounced perlitic structure, and Prof. Watts[2] has remarked that the fine fissures traverse not only the glass but sometimes also the quartz crystals. Prof. Cole[3] has described also lithoidal varieties from Kirkinriola (fig. 47, *B*), Templepatrick, *etc.*, and a microspherulitic one from Cloughwater (fig. 47, *C*). Rhyolites are found again between Dromore and Moira, Co. Down. In the Tertiary rhyolites of Fionn-Choire, in Skye, the ground-mass is partly replaced by streaks and lenticles of quartz[4].

The most interesting British rhyolites, however, are those belonging to the Palæozoic and older volcanic groups, and these have doubtless had their pristine characters modified in many instances by *secondary physical and chemical changes.*

[1] *Journ. Geol.* (1893) i, 176–179.
[2] *Q. J. G. S.* (1894) l, 367–375, pl. XVIII.
[3] *Sci. Trans. Roy. Dubl. Soc.* (1896) vi, 77–118, pl. IV.
[4] *Tertiary Igneous Rocks of Skye* (1904) 59–61.

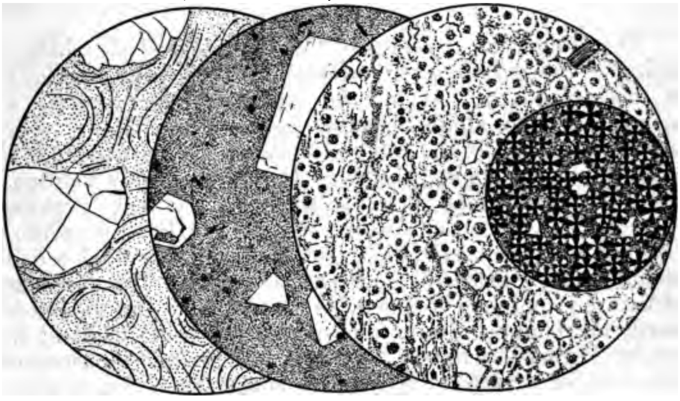

FIG. 47. RHYOLITES, ANTRIM; × 20.

A. Obsidian, Sandy Braes. The phenocrysts are of quartz; the ground-mass a pale brownish glass, crowded with minute felspar microlites, and traversed by perlitic fissures [3636].

B. Rhyolite, Kirkinriola. The phenocrysts are of sanidine and quartz, with a few scattered flakes of biotite and minute crystals of magnetite; the ground-mass a very finely crystalline aggregate of felspar and quartz [3640].

C. Microspherulitic Rhyolite, Cloughwater: consisting essentially of closely packed little spherulites, giving the black cross between crossed nicols, as shown in the small inset circle. The occasional patches of clear quartz are secondary [3638].

Mr Allport was the first to give a clear account of some of the old altered volcanic glasses, and to compare them with fresh Tertiary examples. He described what seems to be a devitrified and altered spherulitic rhyolite of pre-Cambrian age from Overley Hill, or the Lea Rock, near Wellington, Shropshire[1]. A few phenocrysts occur, but the bulk of the rock has been a glass enclosing numerous bands of spherulites. The glass is now devitrified, but perlitic cracks, marked by secondary products, are still evident. The spherulites too

[1] *Q. J. G. S.* (1877) xxxiii, 449–460; Teall, pl. XXXIV, figs. 1, 2.

are for the most part much altered and stained red by iron-oxide.

The Ordovician rhyolites of Caernarvonshire[1] are characterized by the general paucity of any phenocrysts, and especially of those of quartz. Among the scattered felspar-crystals, a member of the albite-oligoclase series predominates over orthoclase. Almost the only ferro-magnesian constituent is a little colourless augite, and even this is commonly wanting, though a pale-green decomposition-product may perhaps represent it. The usual texture of these old lavas is cryptocrystalline to microcrystalline, sometimes showing fluxion and banding, and occasionally good perlitic cracks. The vesicular structure is not very frequent. In some types the ground is partly micropœcilitic, minute felspar prisms being enclosed in quartz (Penmaenbach, *etc.*). Any approach to a microspherulitic structure of a perfect type is uncommon, but large isolated spherulites are abundant in many localities, and show the various secondary alterations, concentric shell-structure, silicification, *etc.*, to which they are always prone[2]. The siliceous and other nodules which thus arise may reach several inches in diameter. Some of them probably represent true lithophyses[3].

Various types of rhyolites, including some with micropegmatite phenocrysts (fig. 46, *B*), occur in the Ordovician of Fishguard in Pembrokeshire[4]; spherulitic and other varieties on Skomer Island[5]; and imperfectly spherulitic types in the Precelli Hills[6]; while examples from Llanrian[7] contain phenocrysts of quartz and orthoclase in a microfelsitic ground-

[1] *Bala Volc. Ser. Caern.* (1889) 18–23. See also Bonney, *Q. J. G. S.* (1882) xxxviii, 289–296, pl. x; Rutley, *ibid.* (1881) xxxvii, pl. xxi, and *Mem. Geol. Sur., Felsitic Lavas* (1885) pl. ii–iv.

[2] *Bala Volc. Ser. Caern.* 35–39; Cole, *Q. J. G. S.* (1885) xli, 162–168, pl. iv, and (1886) xlii, 185–189, pl. ix; Miss Raisin, *ibid.* (1889) xlv, 247–269.

[3] Cole, *Q. J. G. S.* (1892) xlviii, 443–445, with references.

[4] Reed, *ibid.* (1895) li, 162, pl. vi, figs. 3–5.

[5] Rutley, *ibid.* (1881) xxxvii, 409–412; Howard and Small, *Trans. Cardiff Nat. Soc.* (1897) xxviii, part i, with plate.

[6] Parkinson, *Q. J. G. S.* (1897) liii, 465–476, pl. xxxvi.

[7] Elsden, *ibid.* (1905) lxi, 581.

mass. Silicified rhyolites occur at Trefgarn and Roche Castle, near Haverfordwest.

At Malvern (New Reservoir) occur cryptocrystalline (perhaps devitrified) rhyolites, sometimes enclosing scattered phenocrysts of oligoclase. Narrow veins are occupied in some cases by infiltrations of calcite, in others by a clear mosaic of quartz, orthoclase, and plagioclase of secondary formation. Mr Parkinson[1] has described and figured ancient rhyolites with nodular structures representing altered lithophyses from Wrockwardine and Pontesford Hill in Shropshire, as well as from Boulay Bay in Jersey.

Nodular structures, often more or less completely replaced by quartz, are seen also in Westmorland (Great Yarlside). The old rhyolites here resemble in many respects those of like age in Caernarvonshire, but certain flows show a very perfect microspherulitic structure. This is well seen in Long Sleddale[2] and near Great Yarlside. From Dufton Pike, in Edenside, Mr Rutley[3] described and figured rhyolites with a tufaceous structure; and others from the same district show flow brecciation or enclose foreign fragments[4].

Various acid lavas occur in the Ordovician of Ireland. Some from Raheen and other places in Co. Waterford show perlitic and microspherulitic structures[5].

Among the fresh acid lavas of the United States the finest examples of obsidian come from Obsidian Cliff in the Yellowstone Park[6]. In some varieties the glassy matrix contains spherulites of some size, isolated or in bands, and remarkable chambered lithophyses, in which occur nests of tridymite and little crystals of the iron-olivine (fayalite). There are also in the Yellowstone Park finely banded rhyolites, in which the

[1] *Q. J. G. S.* (1901) lvii, 218–223, pl. VIII; see also Boulton, *Q. J. G. S.* (1904) lx, 457–463, on nodular rhyolites from Pontesford Hill; Bonney, *G. M.* (1896) 366, on Boulay Bay, Jersey.

[2] Rutley, *Q. J. G. S.* (1884) xl, pl. XVIII, fig. 6, and *Mem. Geol. Sur., Felsitic Lavas* (1885) pl. II, figs. 1, 2; Teall, pl. XXXVIII [1921].

[3] *Q. J. G. S.* (1901) lvii, 31–37, pl. I.

[4] *Ibid.* (1891) xlvii, 518, 519.

[5] Reed, *ibid.* (1899) lv, 763–766.

[6] Iddings, *7th Ann. Rep. U. S. Geol. Sur.* 249–295; and in Diller, 151–160, pl. XXV–XXVII.

narrow bands differ in microstructure, some being crypto-crystalline, others microspherulitic or axiolitic, *etc.*[1] (fig. 46, *A*).

Zirkel[2] described from Nevada rhyolites (including obsidians) showing a remarkable variety in the character of their ground-mass. Others, from the Eureka district, have been described by Iddings[3]. These carry a little biotite. In examples described by the same author[4] from New Mexico (Tewan Mts) the ferro-magnesian mineral is augite. In these rocks plagioclase felspar is wanting: some contain spherulites and lithophyses. Rhyolites from Custer County, Colorado, have no coloured constituent except a little red garnet[5]. The ground-mass is usually microcrystalline to cryptocrystalline, but sometimes spherulitic. Biotite-bearing rhyolites with porphyritic quartz occur in the Tintic Mts, Utah[6]. Some varieties in the Lassen Peak district, California, are highly spherulitic[7]. Examples from the Black Hills of Dakota have been described by Caswell[8], but Iddings[9] classes some of these rocks as dacites. Rhyolites, some of spherulitic varieties, have been described by Calkins[10] from the John Day basin in Oregon. Here the spherulites are sometimes nearly a foot in diameter, and are then much altered.

Ancient acid lavas of Palæozoic and pre-Palæozoic ages occupy large tracts in the east of Canada and the United States. In spite of alteration they have preserved many relics of original characteristic structures[11]. This is well

[1] See also Rutley, *Q. J. G. S.* (1881) xxxvii, 391–396, pl. xx.

[2] *Micro. Petrogr. Fortieth Parallel* (1876) 163–205, pl. VI–IX.

[3] *Monog.* xx *U. S. Geol. Sur.* (1893) 374–380, pl. VIII; and in Diller, 160, 161.

[4] *Bull. No.* 66 *U. S. Geol. Sur.* (1890) 10, 11.

[5] Cross, *Proc. Colo. Sci. Soc.* 1887, 229–233.

[6] Tower and Smith, 19*th Ann. Rep. U. S. Geol. Sur.* part III (1899) 633.

[7] Diller, *Bull.* 148 *U. S. G. S.* (1897) 192.

[8] *Geol. Black Hills* (1880) 486–488, *etc.*, pl. I, figs. 1, 2.

[9] *Ann. N. Y. Acad. Sci.* (1899) xii, 284–286.

[10] *Bull. Dep. Geol. Univ. Calif.* (1902) iii, 137–141, 152–159, pl. 17, fig. 4.

[11] G. H. Williams, *Journ. Geol.* (1894) ii, 1–31.

illustrated by examples from South Mountain[1] (Penna), which include micropœcilitic, spherulitic, lithophysal, brecciated, and other varieties. Ancient devitrified obsidians and rhyolites, some spherulitic, have been described from Vinal Haven[2], and North Haven[3] in Maine, from near St John, New Brunswick[4], from the Michigamme district in Michigan[5], *etc.*

There are among the acid lavas some characterized by anorthoclase felspar and even soda-bearing pyroxene or amphibole. Some of the ceratophyres and quartz-ceratophyres of certain authors belong here. One from Marblehead Neck, Mass., has phenocrysts of anorthoclase[6]. Another from Baraboo Bluffs, Wis., is also rich in soda[7]. An example from Berkeley, Cal., ranges from a porphyritic variety with microcrystalline ground-mass to a pure glass, but is usually microspherulitic[8]. From the Vieja Mts in Texas Lord[9] describes a quartz-pantellerite with phenocrysts of anorthoclase, augite, and quartz in a ground-mass of ægirine-augite, a brown hornblende (probably barkevicite), orthoclase, and quartz.

In New South Wales a perlitic obsidian from the Tweed River has been described by Smeeth[10], and another from the Macpherson Range contains hypersthene[11]. Better known are the rhyolites of the Hauraki gold-field, in the North Island of New Zealand. Mr Rutley[12] described a number of varieties,

1 G. H. Williams, *A. J. S.* (1892) xliv, 482–496; F. Bascom, *Journ. Geol.* (1893) i, 813–832, and *Bull.* 136 *U. S. G. S.* (1896) with plates. See also Diller, 343–349, pl. XLIII, XLIV.

2 G. H. Williams, *Journ. Geol.* (1894) ii, 23; G. O. Smith, *Joh. Hopk. Univ. Circ.* No. 121 (1895), and *Geol. of Fox Is., Me.* (1896) 46–51, pl. I, figs. 5, 6.

3 Bayley, *Bull. Geol. Soc. Amer.* (1894) vi, 474.

4 Matthew, *Trans. N. Y. Acad. Sci.* (1895) xiv, 197–200, pl. XII, XIII.

5 Clements, *Journ. Geol.* (1895) iii, 811–817.

6 Sears, *Bull. Mus. Comp. Zool. Harv.* (1890) xvi, 162–172. *Cf.* Washington, *Journ. Geol.* (1899) vii, 290–292.

7 Weidman, *Bull. Univ. Wis.* (1895), *Sci. Ser.* i; and in Diller, 164–169, pl. XXVIII.

8 Palache, *Bull. Dep. Geol. Univ. Cal.* (1893) i, 61–72.

9 *Bull.* 148 *U. S. G. S.* (1897) 96.

10 *Journ. Roy. Soc. N. S. W.* (1895) xxviii, 306–320, pl. XLIV–XLVI.

11 Anderson, *Rec. Geol. Sur. N. S. W.* (1902) iii, 47.

12 *Q. J. G. S.* (1899) lv, 451, 462, pl. XXXII–XXXIV, and (1900) lvi, 493–501, pl. XXVII, figs. 1–4.

including obsidians and devitrified obsidians, some perlitic, from Mercury Bay and Tahua or Mayor Island, banded micro-spherulitic rhyolites from Omahu, lithoidal and spherulitic examples from Waihi, *etc.* Other rhyolitic lavas from this district have been described and figured by Prof. Sollas[1], including beautiful spherulitic varieties. About Rotorua and elsewhere in New Zealand the rhyolitic rocks have often suffered by solfataric action, which has resulted in a more or less complete replacement by opal and chalcedony[2].

[1] *The Rocks of Cape Colville Peninsula, Auckland, N. Z.*, 2 vols. (1905–6) with numerous full-page plates.

[2] Compare Rutley, *Q. J. G. S.* (1900) lvi, 501–507.

CHAPTER XII.

TRACHYTES AND PHONOLITES.

THE trachytes are lavas which, with a lower percentage of silica than the rhyolites, have as much or more of the alkalies. The typical *trachytes* consist essentially of alkali-felspars with a relatively small amount of coloured minerals and without quartz. The name trachyte (given by Haüy to denote the rough aspect of the rocks in hand specimens) is used in the older literature to cover all the more acid half of the volcanic rocks. From it have been separated off, on the one hand, the rhyolites of modern nomenclature and, on the other, some hornblende- and mica-andesites, *etc.*

With the trachytes we shall treat some lavas of more peculiar constitution, in which a greater richness in alkalies is connected with the presence of felspathoids as well as alkali-felspars: these are the *phonolites* and *leucitophyres.* The name phonolite (a translation of 'clinkstone,' from the supposed sonorous quality of the rock when struck) seems to have been in general use before the presence of microscopic nepheline in the rock was demonstrated, giving a character of precision to the definition. The original leucitophyres (of Coquand) were apparently any rocks with conspicuous crystals of leucite, but the name is now generally restricted to the types containing an alkali-felspar (sanidine) as an essential constituent. The leucitophyres are a type of extremely restricted distribution, and the unstable nature of the characteristic mineral must make such rocks difficult to detect among the older lavas, a remark applicable also in some degree to the phonolites.

Constituent minerals. Felspars rich in potash or soda are by far the most abundant minerals in the rocks here considered. They occur both as phenocrysts and as the chief element in the ground-mass. The most prominent is usually orthoclase of the *sanidine* variety, often showing a rough orthopinacoidal cleavage. In phenocrysts it has either a tabular or a columnar habit, and both may occur in the same rock. Carlsbad twinning is frequent, and in the larger crystals may show the broken divisional line due to interpenetration. Some degree of zonary banding is sometimes found. The plagioclase felspar which occurs in many trachytes is usually *oligoclase*, but in more basic rocks we may find varieties richer in lime instead. The phenocrysts often show carlsbad- as well as albite-twinning; zonary banding is not uncommon; and parallel intergrowth with sanidine may be noted (fig. 49, *B*).

In the true trachytes the most common ferro-magnesian element is perhaps brown *biotite*, in hexagonal flakes almost always affected by corrosion by the enclosing magma ('resorption'). This is shown by a certain degree of rounding and the formation of a dark or opaque border, or even the total destruction of the flake, the resulting products being especially magnetite and sometimes greenish augite in minute granules. The frequent preservation of the original crystal-forms proves that the process is not one of fusion and re-crystallization, but rather pseudomorphism depending on changed physical conditions and chemical reactions with the fluid magma[1]. Brown *hornblende* is a less frequent constituent, in idiomorphic crystals with similar resorption-phenomena. The *augite*, which is scarcely less common than biotite as a constituent of trachytes, never shows this feature. It is usually pale green in thin slices. In the phonolites and leucitophyres the crystal often shows a deeper tint at the margin, and is almost always sensibly pleochroic (ægirine-augite), a character less common in the trachytes. The soda-pyroxene, *ægirine*, is characteristic of many phonolites and leucitophyres, but only occasionally present in the trachytes. It is green and pleochroic, with a much lower extinction-angle than the augites (5° or less in longitudinal sections). It some-

[1] Washington, *Journ. Geol.* (1896) iv, 257–282.

times grows round a kernel of augite with parallel orientation. The rhombic pyroxene of certain trachytes is always of a deeply coloured and vividly pleochroic variety (*hypersthene* or *amblystegite*), giving red-brown, yellow-brown, and green colours for the several principal directions of absorption.

The *nepheline* of the phonolites and leucitophyres occurs in minute crystals in the ground-mass, having the form of a short hexagonal prism with basal planes, and giving squarish or hexagonal sections (fig. 50). Owing to the small size of the crystals and the optical properties of the mineral, it is liable to be overlooked. Its decomposition gives rise to various soda-zeolites, which occur in nests and veins in many phonolites. The *leucite* of the leucitophyres is always idiomorphic, giving characteristic octagonal and rounded sections (fig. 51, *B*). Twin-lamellation is very frequent in the phenocrysts[1], but the smaller crystals which may occur often behave almost as if isotropic. The leucite may enclose needles of augite and crystals of the earlier-formed minerals, but not of felspar. Minerals of the sodalite group are found in certain trachytes and constantly in the phonolites and leucitophyres. They are almost always in idiomorphic dodecahedra. The *sodalite* is clear when fresh, but often turbid from alteration: zonary structure is frequent. The blue *haüyne* is less often met with, but *nosean* may be very plentiful, usually forming crystals of some size, and always showing more or less plainly its characteristic structure and border[2] (figs. 50, 51, *B*). The sodalite-minerals give rise by alteration to natrolite and other zeolites.

Iron-ores (*magnetite*) occur but sparingly in these rocks. Yellowish *sphene* in good crystals is highly characteristic; and *apatite* is common in colourless needles or sometimes in rather stouter prisms with violet dichroism. The trachytes often contain a little *zircon* in minute prisms.

Among less common minerals may be mentioned the *tridymite* of certain trachytes, in aggregates of minute flakes; *olivine*, as a rare constituent except in certain basic trachytes;

[1] Cohen (3) pl. XXVIII, fig. 4.
[2] Teall, pl. XLI, fig. 1; XLVII, fig. 4.

and *melanite* garnet, which is found in some of the leucitophyres and in certain phonolites as brown isotropic crystals belonging to an early stage of consolidation, sometimes showing marked zonary banding.

As secondary products in trachytic (as also in andesitic) rocks, *opal* and other forms of soluble silica are not uncommon. Normally isotropic, these substances sometimes show double refraction as a consequence of strain, usually about centres, so as to imitate a spherulitic structure. Opal sometimes encloses little flakes or aggregates of tridymite, or is coloured red by included scales of hæmatite. It occurs in the form of veins and irregular knots or patches. Aggregates of minute scales of *tridymite* are common in certain trachytic lavas, such as the 'domites' of Auvergne[1].

Ground-mass. In contrast with the rhyolites, the rocks under consideration have few glassy representatives, and the ground-mass is frequently holocrystalline, or at least with no sensible amount of glassy residue. This is especially true of the typical trachytes, which, with a chemical composition not very different from that of a mixture of felspars, have a strong tendency to crystallize bodily. Fluxional phenomena are not uncommon, but the characteristic banding of the rhyolites is here wanting. Vesicular structure is rare, and perlitic cracks are not found; but, in consequence of the crystalline nature of the ground, with a tendency to idiomorphism in its elements, a miarolitic or drusy structure may be met with. Any structure comparable with the spherulitic is uncommon, though a rough radial grouping of felspar prisms is sometimes observable.

Excepting the nepheline of the phonolites, non-felspathic constituents play in most cases a small part in the ground-mass of the rock here considered. The ground consists, in the trachytes proper, essentially of minute felspars, which may, however, vary somewhat in habit. Most commonly they are 'lath-shaped' microlites, with some degree of parallel disposition in consequence of flow, and this type of ground is so characteristic of these rocks that it is often styled the *trachytic*[2]

[1] Cohen (3), pl. XXXVII, fig. 1.

[2] Berwerth, *Lief.* I (augite-trachyte, Naples).

(fig. 48, *B*). On the other hand the minute felspars may have a shorter and stouter shape, recalling some of the rocks grouped above under the porphyries, and this structure is accordingly designated by Rosenbusch the *orthophyric*[1] (fig. 49).

In some volcanic districts, such as that of the Laacher See, near the Rhine, occur trachytic rocks in which the ground-mass is reduced to very small amount (fig. 48, *C*); and there are some in which ground-mass is wholly wanting. Such rocks,

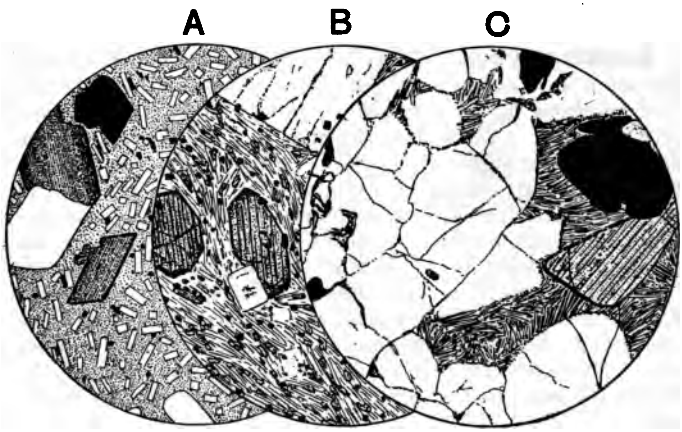

FIG. 48. TRACHYTES; × 20.

A. Hornblende-Trachyte, Grand Sarcoui, Auvergne. Phenocrysts of brown hornblende, magnetite, and oligoclase: ground-mass micro-porphyritic, with little felspar crystals [2816].

B. Augite-Trachyte, Solfatara, Naples. Phenocrysts of pale green augite, sanidine, and some oligoclase: felspathic ground-mass with flow-structure, and enclosing scattered granules of augite and magnetite [1341].

C. Augite-Trachyte or Sanidinite, Laacher See, Eifel. Mainly of clear sanidine, with some oligoclase, augite, magnetite, apatite, and sphene (not shown): the ground-mass reduced to scattered interstitial patches [2507].

[1] Berwerth, *Lief.* II (domite, Auvergne).

composed principally of rather coarsely crystalline sanidine, and known as 'sanidinites' are found as blocks in volcanic tuffs.

Phonolites poor in nepheline do not differ essentially as regards structures from the trachytes; but when the characteristic mineral is plentiful, forming very numerous minute crystals in the ground-mass, the general aspect of the latter is somewhat altered. The leucitophyres show in their very variable structures further departures from the trachyte type, and the porphyritic character is sometimes lost; but all the rocks included in the present chapter resemble one another in being normally holocrystalline.

Leading types. Rocks belonging to the families under discussion have only a very feeble development in this country. True *trachytes* figure very little among the British Tertiary volcanic rocks. A few flows are seen in Fionn-Choire, on the northern border of the Cuillin Hills, Skye[1]. The rock is fine-textured, being composed essentially of little crystals of orthoclase, ·001 inch or less in length, with fluxional arrangement, and some minute octahedra of magnetite. There are scattered phenocrysts of biotite and augite, both decayed. There are also, in Skye[2] and elsewhere, trachyte dykes. Some of these have the ordinary trachytic structure, the felspathic constituents being orthoclase and oligoclase, while in other cases a tendency to radiate disposition on the part of the slender felspars gives a certain spherulitic appearance to the rock.

Trachytic rocks were described by Gen. McMahon[3] from Sourton Tor, on the N.W. border of Dartmoor. There is a ground-mass composed of a felted mass of felspar microlites, with microporphyritic crystals of orthoclase or microperthite and patches of actinolite replacing some destroyed mineral. Better known are the augite-trachytes in the Carboniferous of Haddingtonshire. Under this head Dr Hatch[4] included some

[1] *Mem. Geol. Sur., Tert. Ign. Rocks Skye* (1904) 58.
[2] *Ibid.* 388, 393, 394, pl. XXVII, fig. 1.
[3] *Q. J. G. S.* (1894) l, 345–347.
[4] *Tr. Roy. Soc. Edin.* (1892) xxxvii, 115–126, pl. I, II; see also Geikie, *ibid.* (1879) xxix, pl. XII, figs. 1, 2; and *20th Cent. Atlas*, 46, with plate.

rocks which we have placed under the orthophyres; but others, from the neighbourhood of Haddington, have the characters of trachytic lavas. They consist of alkali-felspars with more or less of a bright to pale green pleochroic augite, doubtless a soda-bearing variety; and contain phenocrysts of sanidine, sometimes with intergrowths of oligoclase, in a holocrystalline ground-mass. The latter is chiefly of sanidine prisms, with a minor proportion of striated felspar. Augite builds imperfect crystals and grains and numerous smaller granules; magnetite occurs sparingly in the same manner; and occasional needles of apatite are seen (fig. 49).

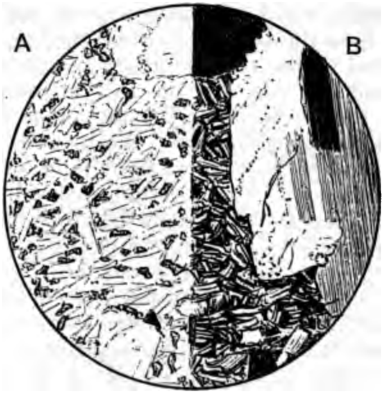

FIG. 49. AUGITE-TRACHYTE, PEPPERCRAIG, HADDINGTON; × 20.

A in natural light, *B* between crossed nicols. Large phenocrysts of felspar are enclosed in a ground composed entirely of little felspar prisms and granules of augite [1980]. The structure is orthophyric.

Lavas consisting almost wholly of alkali-felspars occur at Hamilton Hill and other places near Peebles[1]. Small felspar phenocrysts are embedded in a felspathic ground-mass of microlitic or cryptocrystalline structure, and analysis shows that soda-felspar largely predominates. Such rocks may be termed soda-trachytes.

[1] Teall, *Ann. Rep. Geol. Sur.* for 1896, 40.

Not many trachytes have yet been recorded in America. An example resembling the Drachenfels type (from the Siebengebirge, near Bonn) has been described by Cross[1] from Rosita in Colorado. It is a biotite-trachyte, with phenocrysts of sanidine and smaller ones of oligoclase. The fluxional trachytic ground-mass is essentially of orthoclase, but contains a small quantity of interstitial quartz. Trachytes resembling the Drachenfels type occur also in the Black Hills of Dakota[2], the ferro-magnesian element being sometimes biotite, sometimes hornblende.

For a more complete study of the trachytic lavas we might turn to the volcanic districts of the Rhine, Auvergne, and the west side of Italy, which illustrate a great variety of types. In some rocks from the Laacher See and the neighbourhood of Naples a mineral of the sodalite group becomes a prominent constituent, and we may see in this a transition to the characters of the phonolites. On the other hand, from a study of the old volcanoes of Italy, Washington[3] has proposed the name vulsinite for a group of rocks intermediate between trachyte and andesite. They contain a considerable amount of a basic plagioclase in addition to the alkali-felspar, and the ferro-magnesian constituent is typically augite. In examples from Bolsena in Italy the phenocrysts are of alkali-felspar, anorthite, augite, and biotite, and the ground-mass is of soda-orthoclase, augite, *etc.*, with trachytic structure. One from the Viterbo district has labradorite in place of anorthite. A somewhat more basic type, from the Mti Cimini in the latter district, is styled ciminite[4]. It has the same association of sanidine with a basic felspar, but carries phenocrysts of olivine, as well as of augite and felspar. A well-known example of this is the Arso trachyte, the Ischia lava of A.D. 1302, which approximates in some features to the basalts. The ground-mass is of felspar microlites with interstitial glass, and is sometimes vesicular.

As a comprehensive name for all these lavas intermediate between trachytes and andesites, and representing the volcanic

[1] *Proc. Colo. Sci. Soc.* 1887, 234; and in Diller, 181, 182.
[2] Caswell, *Geol. Black Hills* (1880) 488–492, *etc.*, pl. II.
[3] *Journ. Geol.* (1896) iv, 547–554, 833.
[4] *Ibid.* (1896) iv, 834–838, and (1897) v, 354.

equivalents of Brögger's monzonite family, Ransome[1] has proposed the term 'latite.' The examples which he describes, however, from the western slope of the Sierra Nevada of California, have an abundant glassy base, and alkali-felspars have not crystallized out. A trachytic lava, with phenocrysts of labradorite, from the Cambewarra Range in New South Wales[2] seems to be comparable with vulsinite.

The *phonolites* are usually divided into the 'trachytoid' and the 'nephelinitoid,' the one poor and the other rich in nepheline. The latter may be regarded as the more characteristic phonolites, the former representing a connecting link with the trachytes. Nepheline in only small amount, with interstitial occurrence, is usually difficult to detect without staining[3].

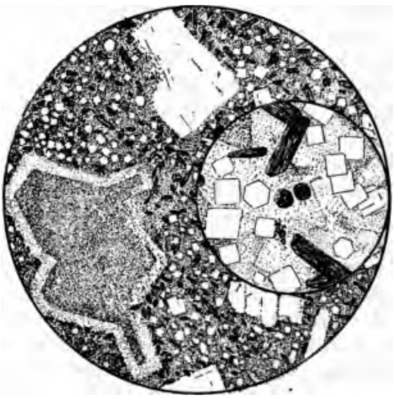

FIG. 50. PHONOLITE, WOLF ROCK, CORNWALL; × 20.

Showing phenocrysts of sanidine and a large crystal-group of nosean, turbid in the interior, in a ground-mass of sanidine, nepheline, and ægirine. These last two minerals are more clearly shown in the small inset circle, × 100 [4930].

[1] *A. J. S.* (1898) v, 355–375; *Bull.* 89 *U. S. Geol. Sur.* (1898).
[2] Card and Jaquet, *Rec. Geol. Sur. N. S. W.* (1903) vii, 109–113.
[3] See Teall, 363, foot-note; *cf.* Cohen (3) pl. LXVI, figs. 3, 4.

In England a thoroughly typical phonolite comes from the Wolf Rock off the coast of Cornwall[1] (fig. 50). It belongs to the nosean-phonolites of some authors, that mineral being found plentifully in it, in addition to nepheline. The nosean occurs chiefly as phenocrysts with a dark interior and clear border[2]. Sanidine is also found as phenocrysts. The general mass of the rock consists of lath-shaped sanidine crystals, more or less idiomorphic crystals of nepheline, and little, dirty green microlites of ægirine. Iron-ores are scarcely represented, and there is little or no residual glass. Other British rocks, which have been designated 'phonolites,' we have already referred to under the head of orthophyres. If admitted here, they would fall under the trachytoid division.

Phonolites are only sparingly represented among the varied volcanic rocks of the United States. One from El Paso County, Colorado[3], is essentially a finely granular aggregate of sanidine, nepheline, and hornblende, with phenocrysts of the two former minerals. A similar rock, with the addition of a little nosean, is known from Black Butte in the Black Hills of Dakota[4]. The felspar phenocrysts are of soda-orthoclase or anorthoclase[5]. Other varieties of phonolites are represented in the same district (fig. 51, *A*). Phonolites occur as volcanic dykes and larger masses in the Cripple Creek mining district, Colorado[6]. They are rich in alkali-felspars, and contain phenocrysts of soda-sanidine or anorthoclase. Nepheline occurs with variable habit, sometimes building small phenocrysts, while porphyritic nosean and minute crystals of sodalite are also found. Ægirine and ægirine-augite are the coloured minerals, or in certain cases a blue amphibole, and among the accessory minerals is analcime, believed to be of primary origin. Osann's rocks from western Texas (Apache type) are rich in hornblende, including a blue variety, and the felspars

[1] Allport, *G. M.* 1871, 247–250, and 1874, 462, 463; Teall, 367, 368, pl. XLI, fig. 1; *20th Cent. Atlas*, 25, 26, with plate.

[2] Teall, pl. XLVII, fig. 4 (misplaced 5 in key-plate).

[3] Cross, *Proc. Colo. Sci. Soc.* 1887, 167, 168.

[4] Caswell, *Geol. Black Hills, U. S. G. and G. Sur. Rocky Mts* (1880) 503-505, pl. I, figs. 3, 4; Cross in Diller, 191–193.

[5] Pirsson, *A. J. S.* (1894) xlvii, 341–346.

[6] Cross, *16th Ann. Rep. U. S. Geol. Sur.* part II (1895), 25–36; Graton, *Prof. Paper* 54 (*U. S. Geol. Sur.*, 1906) 57–67, pl. VII.

show microperthitic intergrowths. Other phonolites from this district are very rich in ægirine and nepheline[1].

Phonolites, both trachytoid and nephelinitoid, are found in the Dunedin district of New Zealand[2]. One variety, with cossyrite in addition to ægirine, has some resemblance to the Apache type.

The *leucitophyres*[3] are a very small group of rocks, known only from a few districts, and best developed in the late Tertiary lavas of the Eifel. The leucite is often of two generations, the larger crystals being frequently of irregular

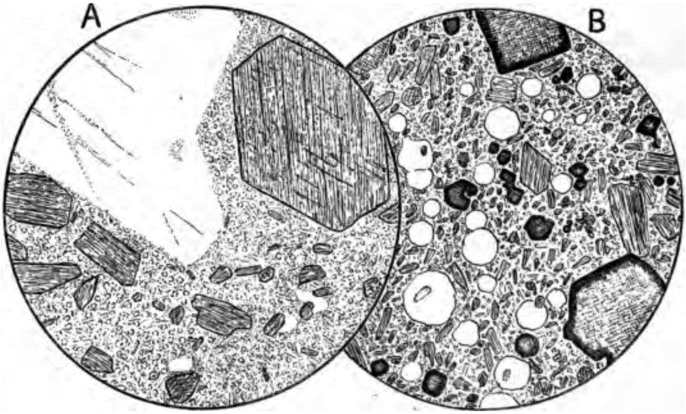

FIG. 51; × 20.

A. Phonolite, Black Hills, S. Dakota. Phenocrysts of soda-sanidine and hornblende in a ground-mass of nepheline and sanidine [3072].

B. Leucitophyre, Burgberg, near Rieden, Eifel. Phenocrysts of green ægirine-augite, dark-bordered nosean, and clear leucite in a ground-mass of ægirine-augite, nepheline, and sanidine [G. 120].

[1] Osann, *4th Ann. Rep. Geol. Sur. Tex.* (1892) 130, 131.

[2] Ulrich, *Trans. Austral. Ass.* (1891) iii, 127–150, pl. v; Marshall, *Q. J. G. S.* (1906) lxii, 401–405.

[3] For figures see Berwerth, *Lief.* IV; Cohen (3), pl. II, fig. 3, IV, fig. 3, and XVI, figs. 1, 2; Fouqué and Lévy, pl. XLVIII, fig. 1 and LI, fig. 1; Teall, pl. XLI, fig. 2 and XLVII, fig. 4; *20th Cent. Atlas*, 27, 28, with plate.

shape. It is always accompanied by nosean and sanidine (fig. 51, *B*). The ferro-magnesian mineral is a green pleochroic augite with zonary banding: the other constituents are sphene, occasionally biotite, and often a little melanite. The structure of the rocks is very variable. In some there is a well-defined ground-mass of minute nepheline, sanidine, augite, and leucite, enclosing phenocrysts of leucite and nosean (Olbrück, *etc.*). In other varieties there is but little sanidine (Schorenberg), while others again have sanidine in large shapeless plates enclosing the other constituents instead of a ground-mass (Perlerkopf). Leucitophyres showing some variety of characters occur at several volcanic centres in Italy[1].

[1] Washington, *Journ. Geol.* (1896) iv, 559–561 (Bolsena), 840–845 (Viterbo); (1897) v, 43 (L. Bracciano), and 248, 248 (Rocca Monfina).

CHAPTER XIII.

ANDESITES.

In this family we include all the lavas of 'intermediate' composition not embraced in the preceding chapter. The name andesite, first used by von Buch and derived from the prevalence of such rocks in the Andes[1], is roughly equivalent to Abich's 'trachydolerite,' implying the intermediate position of these lavas between the acid ones (trachytes of older writers) and the basic (dolerites). The characteristic minerals are a soda-lime-felspar and one or more ferro-magnesian minerals. The alkali-felspars and quartz of the acid rocks are typically absent, as are also the lime-felspar and olivine of the basic rocks. The andesites are distinguished, according to the dominant ferro-magnesian constituent, as *hornblende-*, *mica-*, *augite-*, and *hypersthene-andesites.* Further there is usually recognized a quartz-bearing and more acid division, known as *dacites* or quartz-andesites. Having regard to true lavas, these quartz-bearing andesites seem to be of somewhat limited distribution: many of the rocks described as 'dacites' are of hypabyssal types, and belong to the less acid quartz-porphyries.

Those petrologists who restrict the name andesite to rocks of late geological age, apply to their pre-Tertiary equivalents the name 'porphyrite[2].' Under the same title they include

[1] It should be remarked, however, that the early usage of the word was different, or at least wider, including rocks of plutonic habit (quartz-diorites).

[2] Many also of the rocks designated 'melaphyre' are pyroxene-andesites, others being basalts.

various rocks of hypabyssal types, and it is to these latter that we have already confined the name. Again, certain English petrologists have used the name 'porphyrite' for andesites which have undergone some degree of change by weathering, *etc.*, a distinction which seems scarcely important enough to be recognized in classification or nomenclature.

As regards the general affinities of the family, the dacites have features in common with the rhyolites, the hornblende- and mica-andesites with the trachytes, and the pyroxene-andesites with the basalts, marking thus the intermediate position held among the volcanic rocks by the lavas here considered. As regards the appropriateness of the name, it is remarkable that the lavas of the great volcanic belt of the Andes belong, in so far as they are known, almost exclusively to this family[1].

Phenocrysts. Soda-lime-felspars are the most abundant elements porphyritically developed in these rocks. They include members varying from oligoclase to anorthite, but *andesine* and *labradorite* are the most common. As a rule, the more acid plagioclase belongs to the hornblende- and mica-andesites and dacites, the more basic to the pyroxene-andesites[2]. The crystals, however, are often strongly zoned[3] (fig. 52, *B*), showing a change from a more basic variety in the centre to a more acid at the margin. They are idiomorphic and of tabular habit. With albite-lamellation is frequently associated twinning on the pericline or on the carlsbad law. The commonest inclusions are glass-cavities, either as 'negative crystals,' or rounded: sometimes large irregular cavities occupy much of the bulk of a crystal[4].

The *hornblende* of andesites is in idiomorphic prisms, often twinned. It is usually a brown pleochroic variety with quite low extinction angle, but green hornblende also occurs. The

[1] *Cf.* Iddings, *Journ. Geol.* (1893) i, 164–175.

[2] French petrologists recognize 'andesites' and 'labradorites' as distinct groups, characterized by andesine and labrador-felspar respectively; but this is with reference to the ground-mass.

[3] Iddings, *Monog.* xx *U. S. Geol. Sur.* (1893) pl. v, figs. 1, 3, 4; vi, fig. 2.

[4] Cohen (3), pl. viii, fig. 1.

mica is a brown, strongly pleochroic *biotite* with extinction sometimes sufficiently oblique to show lamellar twinning parallel to the base. Both hornblende and biotite show the same resorption-phenomena[1] as in the trachytes. It is possible that some part of the finely divided magnetite and granular augite in the ground-mass of certain andesites comes from the breaking up of hornblende altered in this way[2]. By decomposition of the ordinary kind the hornblende and mica of andesites give rise to chlorite, magnetite, carbonates, *etc.*

The *augite* is in well-shaped crystals, light green and usually without sensible pleochroism. Twin-lamellation is common. Alteration may give rise to chlorite, epidote, calcite, *etc.* The rhombic pyroxene in the andesites is often *hypersthene*[3], or at least a distinctly coloured and more or less pleochroic variety. It builds idiomorphic crystals, in which the pinacoid faces are more developed than the prism; so that the cross-section is a square with truncated corners, as contrasted with the regular octagon of augite. In longitudinal sections the straight extinction is of course characteristic. The rhombic pyroxene is often converted in the older rocks to bastite.

The *quartz* of the dacites is either in good hexagonal pyramids or more or less rounded and corroded, with inlets of the ground-mass.

Original iron-ores are usually not abundant: *magnetite* is the only one commonly found. Needles of *apatite* occur, and in the more acid andesites little *zircons*[4]. Some of the more basic rocks have sparingly phenocrysts of *olivine*. As occasional accessories may be noted *tridymite* (in druses), *garnet*, and *cordierite*.

Structure of ground-mass. In many andesites the only mineral which occurs distinctly in two generations is

[1] Fouqué and Lévy, pl. XXVIII, XXIX; Zirkel, *Micro. Petrogr. Fortieth Parallel*, pl. V, fig. 2.
[2] Washington, *Journ. Geol.* (1896) IV, 273–278.
[3] Cross, *Bull. No.* 1 *U. S. Geol. Sur.* (1883); *A. J. S.* (1883) XXV, 139; Teall, *G. M.* 1883, 145–148.
[4] Iddings, *Monog.* XX *U. S. Geol. Sur.* (1893), pl. III, figs. 15–20.

the felspar. The felspar of the ground-mass builds little 'lath-shaped' crystals, often simple, sometimes twinned, but usually without repetition. It is probably, as a rule, of a more acid variety than the phenocrysts, labradorite, andesine or oligoclase occurring in different cases. Augite also may be present as a constituent of the ground-mass, forming very small crystals of pale-green tint.

Some of the hornblende- and mica-andesites have a *trachytic* type of ground-mass, composed essentially of very small felspar-laths with little or no glassy base, as in the typical trachytes. It is not always easy to ascertain whether any glass is present or not. From this type, as from the others, there are, however, transitions to rocks with a ground-mass mainly glassy.

Less common is a '*microfelsitic*' or cryptocrystalline structure. This is seen in some of the dacites. In some cases spherulitic structures are found (*cf.* fig. 52, *A*).

In most typical andesites, and especially in the pyroxene-bearing kinds, the ground-mass has the very distinctive 'felted' character termed by Rosenbusch *hyalopilitic*[1]. This consists of innumerable small felspar-laths, simple or once twinned, often with evident flow-structure, and a residuum of glassy matter. Vesicles are common, and their infilling by secondary products gives rise to amygdales[2]. So characteristic is this type, that it is often spoken of as the 'andesitic' ground-mass. When the little felspars are closely packed together, to the exclusion of any glassy base, we have the *pilotaxitic* structure of Rosenbusch. On the other hand, by increase in the proportion of isotropic base, these andesites graduate into more or less perfectly *glassy* forms. Wholly glassy types (andesite-obsidian, including andesite-pumice) are known in small development only, except in so far as they form part of tuffs.

[1] See chromolithograph of augite-andesite ('augite-porphyrite'), Berwerth, *Lief.* I.

[2] Very many of the amygdaloidal lavas (Ger. Mandelstein) belong here; Cohen (3), pl. LXXX, figs. 2–4.

Leading types. Of *dacites*[1] examples occur among the Old Red Sandstone lavas of Scotland, and several have been noticed in the eastern part of Fife. That described by Prof. Judd[2] from Scroggieside is perhaps rather on the border-line between rhyolite and dacite. It has a glassy modification, which the author styles mica-dacite-glass. Phenocrysts of oligoclase and deep brown biotite are embedded in a glassy ground-mass containing trichites, globulites, and imperfect microlites of felspar (perhaps orthoclase). The glass shows beautiful perlitic fissures. Other dacites are recorded from Leuchars and Wormit Bay in the same district[3]. Little is known of true dacites among the Lower Palæozoic lavas of this country, though some of the rocks included above as rhyolites would probably be styled dacites by certain petrologists. The name has also, as remarked above, been applied loosely to some of the acid hypabyssal rocks.

A number of dacites were described from Nevada by Zirkel[4], and some of Richthofen's 'glassy rhyolites' from the same region seem to belong rather to this family[5]. Dacites are also well represented among the Tertiary and Recent lavas in California, Oregon, and Washington, and in San Salvador[6]. Biotite is prominent among the ferro-magnesian minerals, and sometimes hornblende. At Lassen's Peak in California[7] occurs a type rich in phenocrysts, which consist of plagioclase felspar, biotite, hornblende, and quartz, while the ground-mass is essentially of glass (fig. 52, *A*). This is one of the original 'nevadites,' and most of the rocks so styled are probably to be classed as dacites.

In New Zealand, in the Hauraki gold-bearing region of the North Island, Prof. Sollas[8] has described and figured dacites,

1 The name was first used by Stache for quartz-bearing andesites in Transylvania (Dacia).

2 *Q. J. G. S.* (1886) xlii, 427–429, pl. XIII, figs. 7, 8.

3 Flett, *Mem. Geol. Sur. Scot., Geol. E. Fife* (1902) 387.

4 *Micro. Petrogr. Fortieth Parallel* (1876) 134–142: see also Iddings, *Monog.* xx *U. S. Geol. Sur.* (1893) 368–373 (Eureka district), and in Diller, 215–217.

5 Hague and Iddings, *A. J. S.* (1884) xxvii, 460, 461.

6 *Ibid.* (1886) xxxii, 29, 30.

7 *Ibid.* (1883) xxvi, 231–233; Diller, 217–219.

8 *Rocks of Cape Colville Peninsula*, vol. i (1905) 138–147, 164, 197, 201, with full-page plates.

in which hornblende is the ferro-magnesian mineral. Quartz occurs sometimes in corroded grains, as well as in the ground-mass.

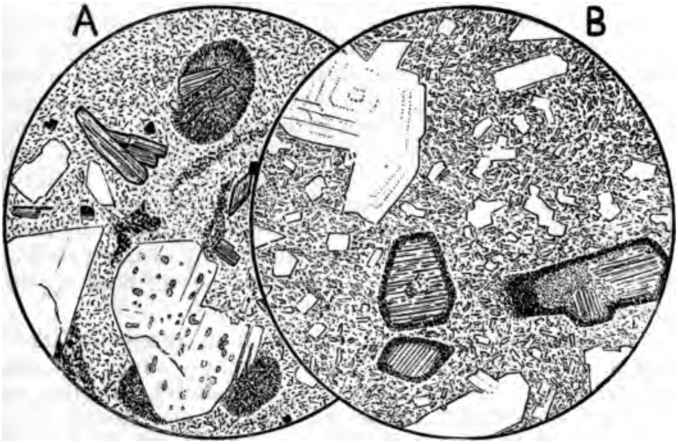

FIG. 52. ANDESITIC LAVAS, CALIFORNIA; × 22.

A. Dacite, Lassen's Peak. The phenocrysts are of andesine (some with large glass-inclusions), hornblende, biotite, and magnetite. In parts of the slide, not figured, quartz, sanidine, and pyroxene occur more sparingly. The ground-mass is a clear glass crowded with little acicular crystallites. There are also growths analogous to spherulites, but with only very imperfectly radiate structure [2800].

B. Hornblende-Andesite, Mt Shasta. The phenocrysts are of hornblende (with resorption-border) and zoned labradorite. The ground-mass consists of little microlites, chiefly of andesine [2802].

Few *hornblende-andesites* are known in the British Isles. One good example occurs on the summit of Beinn Nevis[1], and, though of Palæozoic age, it is fairly fresh. The phenocrysts are of light-brown idiomorphic hornblende and a plagioclase full of glass-inclusions, *etc.* The ground-mass is obscured by specks of iron-ore and alteration-products, but is seen to consist largely of densely packed, minute felspar-microlites.

[1] Teall, pl. XXXVII, fig. 1.

Hornblende-andesites are found in Glencoe, but mostly in a considerably altered state. In particular, they show a development of the red manganese-epidote (withamite) which is seen in the well known 'porfido rosso antico' from Egypt. An andesite with pseudomorphs after hornblende occurs, together with augite-andesites, in the Ordovician volcanic group at Llangynog, near Caermarthen[1]. Again, an Ordovician hornblende-andesite of somewhat basic composition occurs near Kildare[2], and others, brecciated and altered, are found on Slieve Gallion, Co. Londonderry[3].

In America Iddings[4] has recorded mica-andesites, hornblende-mica-andesites, and hornblende-pyroxene-andesites from the Tewan Mts in New Mexico. These rocks have a glassy base. Similar examples come from Lassen's Peak (Cal.), Mt Hood (Ore.), and Mt Rainier (Wash.)[5]. The phenocrysts often show parallel intergrowths of hornblende, augite, and hypersthene. The 'trachytes' of Zirkel[6] and others, in the Great Basin and elsewhere, are in part hornblende-mica-andesites[7]. This type occurs with others at the Comstock Lode[8], and an example with beautifully zoned felspar phenocrysts has been described by Iddings[9] from the Eureka district. Others occur in the Sierra Nevada of California[10]. In these districts hornblende-andesites free from mica are also found, and a good example of this type comes from Mount Shasta, Cal. (fig. 52, *B*). Hornblende- and hornblende-hypersthene-andesites are recorded from the John Day Basin, Oregon[11]. Among the

[1] Cantrill and Thomas, *Q. J. G. S.* (1906) lxii, 243.
[2] Reynolds and Gardiner, *Q. J. G. S.* (1896) lii, 602.
[3] Cole, *Sci. Tr. Roy. Dubl. Soc.* (1897) vi, 222, *etc.*
[4] *Bull. No.* 66 *U. S. Geol. Sur.* (1890) 12–16.
[5] Iddings, 12*th Ann. Rep. U. S. Geol. Sur.* (1892) 610–612, pl. LI: see also Diller, 221–223 (Mt Shasta, Cal.).
[6] *Micro. Petrogr. Fortieth Parallel* (1876) 143–162.
[7] Hague and Iddings, *A. J. S.* (1883) xxvi, 460.
[8] Hague and Iddings, *Bull. No.* 17 *U. S. Geol. Sur.* (1885) 23.
[9] *Monog.* xx *U. S. Geol. Sur.* (1893) 364–368, pl. v, figs. 1, 3, 4 and VI, fig. 2; and in Diller, 219–221.
[10] Turner, 14*th Ann. Rep. U. S. Geol. Sur.* (1894) 487, 488.
[11] Calkins, *Bull. Dep. Geol. Univ. Cal.* (1902) iii, 122–131, pl. 17, figs. 1, 2.

ancient lavas of the United States good hornblende-andesites occur in Minnesota[1].

In a number of andesitic lavas described and figured by Prof. Sollas[2] from the Hauraki gold-mining region of New Zealand, the usual ferro-magnesian minerals are hornblende and hypersthene, severally or together. Both the pilotaxitic and the hyalopilitic types of ground-mass are represented; and the author finds that the place of the glassy base in the latter is taken in the former by a mosaic of quartz. The hornblende shows strong resorption-effects. Hornblende-, as well as augite-, andesites occur on the south coast of New South Wales[3].

Andesites having a pyroxene as their dominant non-felspathic constituent are perhaps more widely distributed than any other group of lavas, and are largely represented among the products of volcanoes now active. Since a rhombic and a monoclinic pyroxene are often associated, the rocks are spoken of as *pyroxene-andesites*, while the marked predominance of one or other of these minerals gives a hypersthene- or an augite-andesite. Hypersthene-andesites, and hypersthene-augite-andesites in which the rhombic pyroxene predominates over the monoclinic, are especially widely distributed among the lavas of different periods.

Pyroxene-andesites are abundant among the older volcanic rocks of Britain. Some in the Lake District contain green pseudomorphs after a rhombic pyroxene (Falcon Crag near Keswick, *etc.*), while many others are characterized by monoclinic pyroxene only. Garnet is a frequent accessory mineral. The micro-structure of the ground-mass is typically hyalopilitic. Numerous examples of these rocks have been described by Clifton Ward, Dr Bonney, Mr Hutchings[4], and Mr Walker[5].

[1] Wadsworth, *Bull. No.* 2 *Geol. Sur. Minn.* (1887) pl. x, xi; Grant, 21*st Ann. Rep. Geol. Sur. Minn.* (1894) 57, 58.

[2] *Rocks of Cape Colville Peninsula*, 2 vols. (1905–6) with numerous full-page plates.

[3] Anderson, *Rec. Geol. Sur. N. S. W.* (1892) ii, 151–154 (Mt Dromedary).

[4] *G. M.* 1891, 539–544.

[5] *Q. J. G. S.* (1904) lx, 70–104.

In the Bala series of Caernarvonshire there are few andesites. Some, with augite only, occur in the Lleyn district[1], and one with dominant hypersthene forms an intrusive mass at Carn Boduan[2] in the same district. The andesites of the Stapeley Hills (Todleth, *etc.*) in Shropshire are of the same general type as the Cheviot rocks, containing both rhombic and monoclinic pyroxenes, and this is true also of the Bala lavas of the Breidden Hills (Moel-y-golfa, *etc.*)[3]. Pyroxene-andesites of Bala age are known at various localities in Ireland; *e.g.* Lambay Is.[4] and Portraine[5].

FIG. 53. HYPERSTHENE-ANDESITE, CHEVIOT HILLS, NORTHUMBERLAND; ×20.

Phenocrysts of labradorite and hypersthene enclosed in a fine-textured ground-mass with a large proportion of glassy base [2762].

Many of the old lavas loosely grouped under the field-term 'porphyrite' in the Old Red Sandstone and Carboniferous of Scotland are andesites, ranging in composition from a relatively

[1] *Bala Volc. Ser. Caern.* 68. [2] *Ibid.* 69–71.
[3] Watts, *Q. J. G. S.* (1885) xli, 539–543; *Proc. Geol. Assoc.* (1894) xiii, 337–339, with figures.
[4] Gardiner and Reynolds, *Q. J. G. S.* (1898) liv, 142–145.
[5] *Ibid.* (1897) liii, 521–527; Sollas, *Pr. Geol. Ass.* (1893) xiii, 100, with fig. 6.

acid type (dacite) to varieties verging on basalt. Some of the former, from North-East Fife, have already been mentioned. In the same district are good examples of more basic types also (Northfield and Causeway Head)[1]. From Dumyat and elsewhere in the Ochils[2] come typical pyroxene-andesites with both hypersthene and augite, the former predominating. The freshest type has an unaltered glassy base, which in other varieties is devitrified. The Old Red Sandstone lavas of the Cheviots[3] are mostly hypersthene-andesites, containing both rhombic and monoclinic pyroxenes. The freshest type shows phenocrysts of labradorite, often honeycombed with inclusions of ground-mass, crystals of hypersthene showing distinct pleochroism, and crystals and grains of pale augite, in a ground-mass of pale brown glass and felspar microlites (fig. 53). The ground sometimes has flow-structure, and shows varieties of the hyalopilitic type. The iron-ores are represented by magnetite and minute red scales of hæmatite. The rock is often veined by opal or chalcedony, stained red with ferric oxide. The more weathered lavas of the district (part of the 'porphyrites' of some authors) have had similar characters, but the felspars and pyroxenes are more or less decomposed, and the ground obscured by ferruginous matter. There are sometimes vesicles, filled with chalcedony, *etc.* Fresh examples come from Kilham, Longknowe, Haddan, and Coldsmouth Hills.

In the Tertiary volcanic series of Britain andesitic lavas play only a very subordinate part. There is, however, a group of dykes and sheets of augite-andesite with a wide distribution. Prof. Judd, who has described examples from Arran[4] and Ardnamurchan[5], points out that they vary between holocrystalline varieties at the one extreme and rocks composed

[1] Judd, *Q. J. G. S.* (1886) xlii, 425–427, pl. XIII, figs. 1, 2: see also Flett, *Mem. Geol. Sur. Scot., Geol. E. Fife* (1902) 386, 387.

[2] Flett, *Tr. Edin. G. S.* (1897) vii, 290–297, pl. XVII; Watts in Geikie's *Ancient Volcanoes* (1897) i, 274–276.

[3] Teall, pl. XXXVI, XXXVII, fig. 2; *G. M.* 1883, 102–106, 146–152, pl. IV, 252–254; Petersen, *G. M.* 1884, 226–234 (*Abstr.*); Watts, *Mem. Geol. Sur. Eng. and Wales, Expl. of Quarter-sheet* 110 *S. W., N. S. sheet* 3 (1895) 12, 13.

[4] *Q. J. G. S.* (1893) xlix, 541.

[5] *Ibid.* (1890) xlvi, 376–378, pl. XV.

mainly of glass at the other. The most characteristic examples contain a notable amount of brown glass, often crowded with crystallites; and this tends to aggregate into patches (fig. 54), or even to collect in round vesicles[1]. Augite-andesites of this group are found in Arran, the Cumbrae Isles[2], Skye[3], Donegal[4], and Northumberland and Durham[5].

FIG. 54. AUGITE-ANDESITE, BRUNTON DYKE, BINGFIELD, NORTHUMBERLAND; ×20.

The only minerals seen are felspar and augite. There are, in addition, interstitial patches of brown glass, which enclose abundant crystallitic growths. The structure is typically 'intersertal' [2359].

The wide distribution of hypersthene-andesites in Europe and America was first insisted upon by Whitman Cross[6], who showed that in a very large number of andesitic lavas hypersthene had previously been mistaken for augite. The rock

[1] Teall, *G. M.* (1889) 481–483, pl. XIV (Tynemouth dyke).
[2] *Mem. Geol. Sur. Scot., Geol. N. Arran* (1903) 119, 120.
[3] *Tert. Ign. Rocks Skye* (1904) 399–401, pl. XXVI, fig. 4, and XXVII, fig. 2.
[4] Sollas, *Sci. Pr. Roy. Dubl. Soc.* (1893) viii, 91–93.
[5] Teall, *Q. J. G. S.* (1884) xl, 209–247, pl. XII, XIII; *Brit. Petr.* pl. XII, XIV.
[6] *Bull. No.* 1 *U. S. Geol. Sur.* (1883); *A. J. S.* (1883) xxv, 139; and in Diller, 224–227.

upon which his first observations were made was from Buffalo Peaks, Colorado. The 'augite-andesites' of Zirkel[1] from Nevada have both rhombic and monoclinic pyroxenes, but the former predominates[2], and true augite-andesites seem to be unrepresented among the lavas of the Great Basin region. Hypersthene-andesites occur in great variety[3] among the Recent lavas of Mt Shasta (Cal.)[4], Mt Rainier (Wash.)[5], *etc.* These are crowded with phenocrysts of zoned plagioclase and pyroxenes, hypersthene predominating over augite, while the ground-mass varies from holocrystalline to vitreous. Andesites carrying hornblende in addition to hypersthene occur in the Eureka district[6], the Sierra Nevada[7], *etc.*

[1] *Micro. Petrogr. Fortieth Parallel* (1876) 221–227, pl. XI, fig. 2.
[2] Cross, *l.c.*; Hague and Iddings, *A. J. S.* (1884) xxvii, 457–460.
[3] Hague and Iddings, *A. J. S.* (1883) xxvi, 222–235.
[4] Diller, 227, 228, pl. XXXII.
[5] G. O. Smith, *18th Ann. Rep. U. S. G. S.* part II (1898) 418–420.
[6] Iddings, *Monog.* xx *U. S. Geol. Sur.* (1893) 348–364, pl. VII, fig. 1.
[7] Turner, *14th Ann. Rep. U. S. Geol. Sur.* (1894) 488; and *17th Ann. Rep.* (1897) 617–619, pl. XLV. fig. *A*.

CHAPTER XIV.

BASALTS.

In the *basalt* family we include all the basic lavas except those in which there is a relatively high content of alkalies due to the presence of minerals of the felspathoid group. The rocks range in texture from vitreous to holocrystalline. Except in a few of the latter (*dolerites*), the distinction between phenocrysts and ground-mass is commonly well marked, but the relative proportions of the two vary greatly in different types. The characteristic minerals in this family of rocks are a felspar rich in lime, augite, and olivine.

Following our principle, we shall make no distinction, as regards nomenclature and classification, between Tertiary and pre-Tertiary lavas. Foreign petrologists usually restrict the names basalt and dolerite to the newer examples, their older equivalents being denoted by such names as melaphyre, augite-porphyrite, diabase, *etc.*, some of which are also applied to rocks of the hypabyssal division.

Constituent Minerals. The felspars of the basalts are of decidedly basic varieties. When distinctly porphyritic crystals occur, they seem to be usually *bytownite* or *anorthite*, while the felspars of the ground-mass are more commonly *labradorite*. The phenocrysts show albite-lamellation, often combined with pericline- and carlsbad-twinning. Zonary structure and zonary arrangement of glass-cavities are met with. The felspars of the ground-mass have the lath-shape, and are commonly too narrow to show repeated twinning. Orthoclase is found only in certain abnormal types.

The dominant pyroxenic constituent is an ordinary *augite*, and this too may occur in two generations. If so, the phenocrysts often have good crystal-forms, with octagonal cross-section: twinning is frequently seen, and sometimes zoning and hour-glass structure. The colour is usually very pale, brownish or more rarely greenish, the latter especially in the interior of a crystal. The augite of the ground-mass is either in little idiomorphic prisms or in granules, and is often very abundant. Decomposition of the augite produces chloritic substances, *etc.* A rhombic pyroxene, *hypersthene* or bronzite, occurs only in certain basalts, where it seems to some extent to take the place of olivine. It is always in idiomorphic prisms, and in the older rocks is very generally serpentinized. Some basalts, again, contain corroded crystals of *brown hornblende*, and others a little *brown mica*.

In the greater number of the basalts *olivine* is an essential constituent, and in many it is abundant, though confined, as a rule, to phenocrysts. These are sometimes well shaped crystals, sometimes more or less rounded, while in certain of the more glassy rocks hollow or skeleton crystals and crystallites occur[1]. The mineral is colourless in thin sluices. It often shows serpentine-strings following cleavage- or other cracks, and with further alteration passes into various secondary products, serpentine, carbonates, *etc.* Another common change is the production of a red or brown margin to the olivine, due to iron-oxide. Another mode of alteration sometimes met with results in the formation of brown pleochroic pseudomorphs of a mineral with a perfect cleavage and the appearance of a mica. It seems to agree in general characters with the mineral described in California by Lawson[2] under the name iddingsite; but the author named, regarding this as an original constituent, has made it the characteristic of a new group of lavas (carmeloites).

Octahedra and grains of *magnetite* are generally abundant, and this mineral frequently recurs in a second generation in little granules. Besides this, there are frequently little opaque or deep brown scales of *ilmenite* or deep red flakes of

[1] Cohen (3) pl. I, fig. 3; XIV, fig. 2.
[2] *Bull. Geol. Dep. Univ. Cal.* (1893) i, 29–46, pl. IV.

hæmatite. Grains of *native iron* occur locally in a few basalts (Ovifak in Disco, Greenland)[1].

Of other common minerals we need note only *apatite*, forming long needles, either colourless or of a faint violet or bluish tint.

Structures. The rocks of the basalt family present a wide range of characters, from purely glassy examples at one extreme to wholly crystalline at the other. Rocks exhibiting such a range may occur, perhaps exceptionally, in one district, their petrological characters being correlated with their various modes of occurrence, as is well described by Prof. Judd[2]. On the whole, the tendency to crystallization is much stronger here than in the more acid families of lavas. Again, the order of crystallization of the several constituents is less strongly marked, the mutual relations between augite and felspar, in respect of priority, varying, while the iron-ores, though they commonly begin to crystallize at an early stage, may be in part rather late. These remarks are true of both the 'intratelluric' and the 'effusive' periods, when these are distinctly separable; but in some of the holocrystalline types the porphyritic character is not recognizable.

Except in the form of lapilli and fragments in tuffs, the purely vitreous type, *tachylyte*, is of very limited distribution, being found commonly as a very thin crust on some lava-flows or a narrow selvage to basalt-dykes. It consists of a brown or yellow glass densely charged with a separation of magnetite[3]. This is sometimes in globulites[4] disseminated through the glass so as to render it almost opaque, or collected in cloudy patches (cumulites); at other times it forms trichites or crystallites of minute size[5]. Perlitic structure is less common than in the obsidians. Interesting spherulitic structures are met with in some examples[6]. When distinct phenocrysts occur abundantly in the glassy ground-mass, we have what is

[1] Fouqué and Lévy, pl. XXXVI, fig. 2; Steenstrup, *M. M.* i, 148, pl. VI.
[2] *Q. J. G. S.* (1886) xlii, 66–82, pl. V, VI.
[3] Cohen (3), pl. XXXIX, figs. 1, 2.
[4] *Ibid.* pl. VI, fig. 4; IV, fig. 2.
[5] Judd and Cole, *Q. J. G. S.* (1883) xxxix, pl. XIV.
[6] Cole, *ibid.* (1888) xliv, 300–307, pl. XI.

sometimes called the 'vitrophyric' structure. The basic glass is subject to alteration, probably involving, as a rule, hydration and other chemical changes; but the resulting substance, known as palagonite, is still an isotropic glass, yellow, brown, or sometimes green in sections.

Radiate aggregates of felspar microlites or fibres, answering to the spherulites of acid rocks, occur in some basaltic glasses, which are known as *variolites*. These aggregates vary in size and in the regularity of their structure, which ranges from mere fan-like and sheaf-like groupings to spherules with a perfect radiate structure. They may occur isolated in a glassy matrix, or coalesce into bands, or form a densely packed mass with little or no interstitial matter. The variolites are very susceptible to alteration.

Leaving the glassy basalts, we note those in which the ground-mass enclosing the phenocrysts of olivine, augite, felspar, *etc.*, is *hypocrystalline*, consisting of lath-shaped felspar-microlites and granules or microlites of augite with more or less of a residual glassy base. Of this division there are various types, depending on the relative proportions of augite, felspar, and glass, and the mutual relations of the minerals. When the felspar-microlites preponderate, usually with a more or less fluxional arrangement, the ground-mass does not differ essentially from the 'hyalopilitic' type so common in the pyroxene-andesites. Vesicles are frequent in such rocks. More often, however, augite is abundantly represented in the basaltic ground-mass. Again, unindividualised glass may form the bulk of the ground. Another type of structure, already noticed in the pyroxene-andesites, is the intersertal, in which a hypocrystalline or glassy ground-mass occurs only as angular patches in the interstices of the abundant phenocrysts.

By the failure of the glassy residue we pass to those types of basalt in which the phenocrysts are enclosed in a *holocrystalline* ground-mass. Here again there are numerous varieties. Sometimes little eye-like or lenticular patches relatively rich in augite are contrasted with adjacent patches rich in felspar. When felspar-microlites make up a large part of the ground-mass, we have a structure analogous to the 'pilotaxitic' of some andesites and trachytes, the flow

being more or less marked. On the other hand, the ground-mass may consist mainly of small rounded granules of augite, between which the little felspars seem to be squeezed (fig. 55). A typical ophitic structure is exceptional; and, on the other hand, augite with idiomorphic shape is seldom found in the ground-mass of the basaltic lavas.

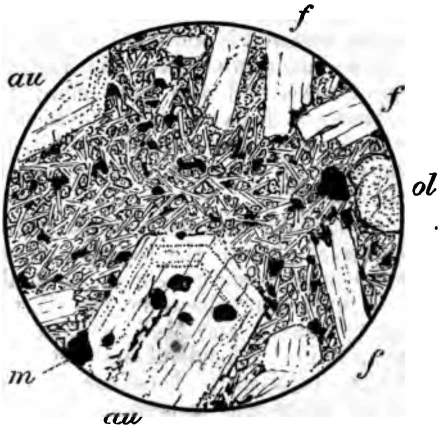

FIG. 55. OLIVINE-BASALT, ETNA LAVA OF 1669 ERUPTION, CATANIA; × 20.

Showing phenocrysts of zoned augite (*au*), felspar (*f*), olivine (*ol*), and magnetite (*m*) in a holocrystalline ground-mass of little lath-shaped felspars and granules of augite and magnetite [131].

Many Tertiary and Recent basalts in Germany, Auvergne, and other regions enclose so-called '*olivine-nodules*,' which are hypidiomorphic aggregates of olivine with enstatite, diopside, *etc.*[1] By some they have been regarded as very early intratelluric formations from the magma, by others as actual enclosed pieces of peridotites. Such nodules are not found in the British Tertiary basalts.

Leading types. The Tertiary basaltic lavas of Britain, as developed in the Inner Hebrides and in various parts of the

[1] Fouqué and Lévy, pl. XI., fig. 1.

west of Scotland and the north of Ireland, are in great part *olivine-basalts*[1]. Varieties with glassy base are not of frequent occurrence. An amygdaloidal structure is very general, and the most common contents of the amygdales are minerals of the zeolite group[2]. A few of the rocks are conspicuously porphyritic, the felspar occurring in two generations, of which the earlier is a thoroughly basic variety, sometimes near anorthite, while the latter is less basic, usually labradorite. Porphyritic augite, however, is not found, and this distinguishes the group of rocks in question from the Tertiary basalts of various European areas and also from many Carboniferous basalts of Scotland and Ireland. The augite of the groundmass has most commonly the granulitic habit, but examples are not wanting in which the ophitic type of structure is more or less perfectly realised.

The name *tachylyte* is commonly employed to cover the glassy representatives of both the basalts and the pyroxene-andesites, besides other basic glasses richer in alkalies. Examples occur at numerous places in the Tertiary volcanic districts of Skye[3], Raasay, and Mull[4], and in the Co. Down (Slievenalargy)[5]; while a considerable variety of occurrences is found in the Isle of Muck[6]. These are all selvages, not of lava-flows, but of dykes and sometimes sheets. The rocks usually enclose small crystals of magnetite and sometimes of olivine, augite, and felspar. The glass is crowded with incipient growths of magnetite and occasionally of other minerals. These take the form of globulites, sometimes collected into cumulites (the Beal in Skye), of margarites (Lamlash near Arran), or of numerous minute opaque rods (Sorne in Mull, *etc.*), sometimes accompanied by transparent crystallites and belonites (Gribun in Mull). Spherulites occur in some instances (Ardtun in Mull[7] and various occurrences in

[1] *Mem. Geol. Sur., Tert. Ign. Rocks Skye* (1905) 32–38, pl. xvii, figs. 1–3. [2] *Ibid.* 41–46.

[3] *Ibid.* 333–350, pl. xxiii and xxiv, fig. 1; Judd and Cole, *Q. J. G. S.* (1883) xxxix, 444–462, pl. xiii, xiv.

[4] Heddle, *Tr. G. S. Glasg.* (1895) x, 81–85. For localities of numerous other examples in Mull, see Kendall, *G. M.* 1888, 555–560.

[5] Rutley, *Journ. Roy. Geol. Soc. Ire.* (1877) iv, 227–232, pl. xiv.

[6] *Geol. Small Is., Mem. Geol. Sur. Scot.* (1907) ch. xiii, pl. viii.

[7] Cole, *Q. J. G. S.* (1888) xliv, 300–307, pl. xi.

Skye), sometimes packed together, with polygonal boundaries, to the exclusion of any glassy matrix.

Closely allied to the spherulitic tachylytes are the rocks known as *variolite*, of which examples have been described from Tertiary dykes in the neighbourhood of Annalong, Co. Down[1], the Point of Sleat in Skye[2], and the headland of Ardmuchnish, Argyllshire[3]. The spherules show considerable variety of structure, ranging from mere fan-like groupings of felspar microlites, or sheaf-like aggregates with a lath-shaped crystal as nucleus, to very regular, radiate, spherulitic growths. They may be closely packed to make up the entire mass of a portion of the rock, or arranged in bands, or isolated in a matrix of brown or greenish glass with cumulites, globulites, *etc.* The individual spherules are commonly from one-tenth to one-half of an inch in diameter, but sometimes less or more. Secondary changes may cause devitrification of any glassy matrix, and give rise to a separation of iron-oxides, a production of epidote, *etc.* An example remarkable alike for the large scale of its structure and the perfection of its preservation is that from the Point of Sleat in Skye. Here the spherules, sometimes as much as two or three inches in diameter, are built of radiating felspar fibres with minute skeleton crystals of olivine and granules of augite, while in one variety of the rock there is a considerable amount of interstitial glassy base.

The basic lavas of Carboniferous age in this country are also characteristically olivine-bearing rocks. Those of Derbyshire (to be distinguished from the ophitic olivine-dolerites of intrusive habit) are *porphyritic olivine-basalts* with olivine and large augite phenocrysts in a ground-mass of small felspar laths, augite grains and prisms, and iron-ores,

[1] Cole, *Sci. Pr. Roy. Dubl. Soc.* (1892) vii, 511–519, pl. XXI; (1894) viii, 220–222.

[2] Clough and Harker, *Tr. Edin. G. S.* (1899) vii, 381–389, pl. XXIII; *Tert. Ign. Rocks Skye*, 346, 347, pl. XXIII, fig. 2.

[3] Bailey, *Tr. Edin. G. S.* (1905) viii, 363–371, pl. XI. For other British variolites see Miss Raisin (Lleyn), *Q. J. G. S.* (1893) xlix, 145–159, pl. I; Cole (Careg Gwladys, Anglesey), *Sci. Proc. Roy. Dubl. Soc.* (1891) vii, 112–120, pl. X; Sollas (Roundwood, Co. Wicklow), *ibid.* (1893) 99–106, figures; Lloyd Morgan and Reynolds (Bristol), *Q. J. G. S* (1904) lx, 152, pl. XVII, fig. 3. For coloured figure of the 'variolite of the Durance' see Fouqué and Lévy, pl. XXIV, fig. 2.

with little interstitial matter (Blackwell Lane, Great Low)[1]. The basalts of the Bristol district have been described by Professors Lloyd Morgan and Reynolds[2]. The lavas of Kelso, in the Lower Carboniferous of the Cheviot district, are olivine-basalts with phenocrysts of anorthite. One from Stichill in Roxburghshire was described by Dr Teall[3]. In other examples, from Northumberland, Prof. Watts[4] notes brown pleochroic pseudomorphs after olivine, which he identifies with iddingsite. The Carboniferous olivine-basalts of southern Scotland present collectively a considerable variety of characters[5]. The commonest type has rather abundant small olivines and grains of augite in a mesh of slender felspars with microlitic augite and minute granules of magnetite (Dalmeny, Bathgate Hills, *etc.*). In another type the olivine phenocrysts are large, and the felspar microlites are found only in small amount (lowest lavas of Bathgate Hills, Linlithgowshire). A well-known rock from the Lion's Haunch on Arthur's Seat, Edinburgh[6], has numerous large, well-built crystals of augite, olivine, and felspar, with small crystals of magnetite, in a ground-mass of little crystals and microlites of felspar, granules of augite and magnetite, and some residual glass. In the lava of Craiglockhart Hill the ground-mass is more glassy, while the phenocrysts are augite and olivine without felspar. On the other hand, there is a holocrystalline type, which is an olivine-dolerite with granulitic to sub-ophitic structure (Gallaston, N.W. of Kirkcaldy). A curious variety, very rich in felspar, comes from Markle quarry in the Garlton Hills, Haddingtonshire[7].

[1] Arnold-Bemrose, *Q. J. G. S.* (1894) l, 624; *Pr. Geol. Ass.* (1899) xvi, 213, 214.

[2] *Q. J. G. S.* (1904) lx, 151–153.

[3] *G. M.* (1883) 258–260, pl. VI.

[4] *Mem. Geol. Sur. Engl. and Wales, Expl. Quarter-sheet* 110, *S. W.*, *N. S. sheet* 3 (1895) 14.

[5] Geikie, *Q. J. G. S.* (1892) xlviii, *Proc.* 105, 106; Watts in Geikie's *Ancient Volcanoes* (1897) i, 418, and *Ann. Rep. Geol. Sur.* for 1896, 64, 65; Falconer, *Tr. Roy. Soc. Edin.* (1906) xlv, 134–136, pl. I (Bathgate and Linlithgow Hills).

[6] Teall, pl. XXIII, fig. 1; *20th Cent. Atlas*, 13, 14, with plate. A similar rock occurs at Kippielaw, near Haddington, and elsewhere in the East Lothian district; also in the Isle of Man (Stack of Scarlet), see Hobson, *Q. J. G. S.* (1891) xlvii, 443, 444.

[7] Hatch, *Trans. Roy. Soc. Edin.* (1892) xxxvii, 119, pl. I, fig. 2.

Here olivine occurs only in small sporadic grains, while phenocrysts of labradorite are numerous, and the ground-mass consists of laths, microlites, and granules of felspar with dispersed magnetite and probably only a little augite. This variety, which recurs in other places, evidently stands somewhat apart from normal basalts. It has affinities with the Mugeary type, as represented by intrusive sills in the Tertiary series of Skye, *etc.* (see above, p. 147).

Basalts devoid of olivine are apparently not very common among the British Carboniferous volcanic rocks; but they seem to have a rather wide distribution among the Old Red Sandstone lavas in some parts of Scotland[1].

The basic lavas of the English Lake district are wholly free from olivine. They usually carry a rhombic as well as a

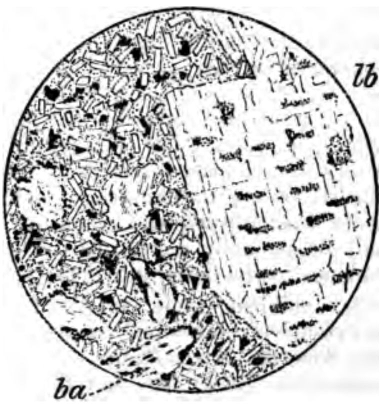

FIG. 56. HYPERSTHENE-BASALT, EYCOTT HILL GROUP, MELMERBY, CUMBERLAND; × 20.

To the right is one of the large crystals of labradorite (*lb*) with its peculiar inclusions. The hypersthene is represented by bastite pseudomorphs (*ba*): augite occurs in less abundance. These, with the little felspar-prisms, the granules of magnetite, and some residual glassy base, make up the bulk of the rock [1251].

[1] Peach and Horne, *Tr. Roy. Soc. Edin.* (1884) xxxii, 379, 380, pl. XLV, figs. 1, 2 (Shetland).

monoclinic pyroxene, and here, as in some other families, hypersthene may be considered as, to some extent, taking the place of the more basic silicate olivine. Such rocks may be termed ***hypersthene-basalts***. The hypersthene is always converted into a light green, pleochroic, serpentinous substance comparable with bastite. The most striking variety, represented at Eycott Hill[1] and numerous other localities in the district and at Melmerby[2] near Cross Fell, has large rounded phenocrysts of labradorite (fig. 56) with carlsbad and albite-twinning. These contain rather large opaque inclusions in the form of negative crystals and smaller enclosures with zonary disposition. In other varieties of the lavas these large crystals are not present. The ground-mass consists of slender striated prisms of plagioclase, crystals of hypersthene converted to pleochroic bastite, granules of augite, abundant magnetite, and an isotropic base.

Olivine-basalts do not figure largely in the great volcanic groups which characterize the Lower Palæozoic in various parts of Britain. Sir A. Geikie[3] has noted olivine-basalts of early Cambrian (or late pre-Cambrian) age near St David's (Rhosson, Clegyr Foig, *etc.*). The idiomorphic crystals of olivine in these rocks are replaced largely by hæmatite. The ground-mass consists of augite-granules, abundant octahedra of magnetite, and a base crowded with globulites and trichites, felspar being only occasionally recognized. These characters suggest a resemblance to the limburgite type (p. 158).

Olivine-basalts, exhibiting some variety of microstructure (see fig. 57), are extensively developed among the lavas of late geological age in America; for instance, in the Great Basin region, lying between the Rocky Mts and the Sierra Nevada. Here they are mostly porphyritic, with relatively large phenocrysts of olivine, plagioclase, and occasionally augite, in a glassy, microlitic, or microcrystalline ground-mass. A smaller number are non-porphyritic, consisting of a uniform aggregate

[1] Ward, *Monthly Micro. Journ.* (1877) xvii, 240–245; Bonney, *G. M.* 1885, 76–80; Teall, 225–227.

[2] *Q. J. G. S.* (1891) xlvii, 517.

[3] *Ibid.* (1883) xxxix, 304, pl. IX, fig. 4. On basalts from Skomer Is. see Howard and Small, *Tr. Cardiff Nat. Soc.* (1897) xxviii, part I, with plate.

A B C

FIG. 57. OLIVINE-BASALTS, U.S.A.; × 20.

A. Near Flagstaff, Arizona [4147].

B. Rio Puerco, New Mexico; with patches of dark glassy base [1434].

C. Near Sierra City, Sierra Nevada, California; with conspicuous crystals of felspar and augite, as well as olivine [3473].

of plagioclase, augite, olivine, and magnetite, often with a considerable amount of glassy base[1]. Other examples have been described from the Sierra Nevada[2], the Tewan Mts (N.M.)[3], and San Salvador[4]. In the latter region it has been remarked that the varieties poor in olivine carry hypersthene in addition to augite. Recent olivine-basalts occur at many localities in Colorado, New Mexico, Arizona, and about Mt Shasta and Lassen's Peak in California. Hypersthene-basalts are likewise represented among the Tertiary lavas of the western United States. Examples have been noted by Iddings[5] from the Eureka mining district in Nevada.

[1] Hague and Iddings, *A. J. S.* (1884) xxvii, 456, 457; *cf.* Zirkel, *Micro. Petr. Fortieth Parallel* (1876) 229–254; pl. x, figs. 1, 3, 4; xi, fig. 3.

[2] Turner, 14*th Ann. Rep. U. S. Geol. Sur.* (1894) 490–492.

[3] Iddings, *Bull. No.* 66 *U. S. Geol. Sur.* (1890) 16.

[4] Hague and Iddings, *A. J. S.* (1886) xxxii, 27, 28.

[5] *Monog.* xx *U. S. Geol. Sur.* (1893) 386–394, pl. vii, fig. 2.

Basic lavas of greater geological antiquity, and more or less modified by secondary changes, have been described from Nôtre Dame Bay in Newfoundland[1], North Haven in Maine[2], South Mountain in Pennsylvania[3], the Penokee (Huronian) group[4], Keweenaw Point, *etc.* (Mich.), and other localities in the Lake Superior region[5], the Grand Cañon of the Colorado[6], and other districts of pre-Cambrian and Lower Palæozoic rocks.

Amygdaloidal basalts, mostly without olivine, occur in force in various parts of South Africa, *e.g.* the Drakensberg range[7],the Victoria Falls neighbourhood[8], *etc.* Zeolites occur abundantly in the cavities, as is also the case in the extensive amygdaloidal basalts of the Deccan in India. In Australia basaltic lavas have been studied in New South Wales (Bathurst, *etc.*[9]) and in various districts of Victoria. From North Gippsland, Vict., Howitt[10] has described Palæozoic basalts with amygdaloidal cavities containing various secondary products. Tachylytes are known from North Gippsland[11] and from Carcoar, N.S.W.[12]; and an example with large radiate spherulites occurs at Elsmore in the latter colony.

[1] Wadsworth, *A. J. S.* (1884) xxviii, 95.

[2] G. O. Smith, *Joh. Hopk. Univ. Circ.* No. 121 (1895).

[3] G. H. Williams, *A. J. S.* (1892) xliv, 490–492.

[4] Van Hise, *Monog.* xix *U. S. Geol. Sur.* (1892) 410.

[5] Pumpelly (Irving), *Copper-bearing Rocks, etc., Monog.* v *U. S. Geol. Sur.* (1884) 69–77, pl. ix.

[6] Iddings, *14th Ann. Rep. U. S. Geol. Sur.* (1894) 520–524.

[7] Schwarz, *Ann. Rep. Geol. Comm. C. G. H.* for 1902, 66–96.

[8] Mennell, *G. M.* 1902, 358, 359.

[9] Curran, *Journ. Roy. Soc. N. S. W.* (1891) xxv, 195–208, pl. xxi; Ross, *ibid.* (1868) xxxi, 302–312.

[10] *Rep. Progr. Geol. Sur. Vict.* (1877) 80–94, pl. i. On other Victorian basalts see *ibid.* (1878) 113–115 (Bogong and Dargo).

[11] Howitt, *ibid.* (1878) 138, pl. ii, fig. 1.

[12] Curran, *l.c.* 212, 213, pl. xx.

CHAPTER XV.

LEUCITE- AND NEPHELINE-BASALTS, ETC.

We shall group together for convenience various basic and ultrabasic lavas in which leucite, nepheline, and sometimes melilite are prominent constituents, with or without a lime-soda-felspar. In the phonolites and leucitophyres, described above, a potash-felspar was an essential mineral, and the rocks had other affinities with the trachytes. Although some of the rocks to be noticed resemble the phonolites and leucitophyres in some features, they are for the most part allied rather with the basalts, being in all cases rocks of low acidity.

Those types in which leucite or nepheline only partly takes the place of felspar are termed *leucite-* or *nepheline-tephrites* when free from olivine, and *leucite-* or *nepheline-basanites* when containing that mineral. For those rocks which have the felspathoid minerals to the exclusion of felspar the name *leucitite* or *nephelinite* is used when olivine is absent, and *leucite-* or *nepheline-basalt* when olivine is present. In all these divisions the leucite-bearing and the nepheline-bearing types are on the whole distinct, though the rocks characterized by either of the minerals may contain the other as an accessory.

The rocks here noticed are known chiefly from districts of Tertiary and Recent volcanic rocks. A few examples of Palæozoic age have, however, been recorded: leucite-tephrite from the Maconnais, leucitite from Siberia, *etc.*

Constituent minerals. The *leucite* of these rocks may be in two generations, differing in size. The crystals are always idiomorphic icositetrahedra, but often more or less rounded. They usually show feeble birefringence and the characteristic lamellar twinning[1]. Augite microlites and granules, glass-inclusions, *etc.*, are often arranged in zones, or grouped in the centre of the crystal[2].

The *nepheline* in the porphyritic types is usually confined to the ground-mass. In the nephelinites and nepheline-basalts it is commonly idiomorphic, except in some of the holocrystalline rocks. In other types it often forms small allotriomorphic crystals, not easily identified, and its distribution may be local. It can sometimes be made evident by staining with fuchsine. The common alteration-products are natrolite and other soda-zeolites in radiating aggregates.

Other felspathoid minerals, *sodalite*, *haüyne*[3], and *nosean*, are not uncommon as phenocrysts in the rock-types richest in leucite and nepheline, but they occur only as accessories.

The yellow or colourless *melilite*[4] is recognized by its weak double refraction, straight extinction, and peculiar microstructure. Idiomorphic crystals have a tabular habit parallel to the base, and the basal faces sometimes form concave curves. The mineral may also be quite allotriomorphic, and, when it occurs as an accessory in leucite-lavas, has sometimes the form of a framework enclosing other minerals in pœcilitic fashion (fig. 59).

This latter mode of occurrence is sometimes seen also in the *sanidine* which occurs as an accessory in some of the leucite- and nepheline-lavas, linking them with the leucitophyres and phonolites. The *plagioclase* felspars, which are found in some types of these rocks, are always of a basic variety. There may be phenocrysts with idiomorphic outline, tabular habit, albite-lamellation, zonary structure, and zones of glass-inclusions; while the felspars of the ground-mass vary

[1] Cohen (3), pl. XXVIII, fig. 3.
[2] *Ibid.* pl. VII, fig. 1; XIV, fig. 1; XVII, fig. 2; XIX, fig. 1.
[3] *Ibid.* pl. XXI, fig. 3.
[4] For good figures see Stelzner, *Neu. Jahrb.*, *Beil.* Bd. ii (1882) pl. VIII.

from narrow laths, often only once twinned, to mere microlites. These show a tendency to spherulitic arrangement, and the phenocrysts too may form radially grouped aggregates (fig. 58).

The usual coloured constituent in the rocks here considered is *augite*. It often occurs in two generations, the earlier relatively large and well shaped[1]. The colour is commonly green, but often varies in concentric zones[2], becoming sometimes pale violet, with distinct pleochroism, at the margin of a crystal. Again, there are sometimes two kinds of porphyritic augite, differently coloured. Some nephelinites have a purple-brown pleochroic, 'hour-glass' augite (fig. 60). Exceptionally some of the rocks contain little yellowish-green needles of *ægirine*. A brown or red-brown or red *biotite* is very common in the nepheline- and melilite-rocks, often showing resorption-phenomena. Brown *hornblende* is an occasional accessory in some rocks, and commonly shows a corrosion border of magnetite and augite[3].

Olivine is an essential constituent in many of the types, and has the same general characters as in basalts. In some of the most basic rocks the mineral is a hyalosiderite, and often becomes red by the separation of iron-oxide.

Iron-ores are commonly present, and in the olivine-bearing rocks often abundant. They are *magnetite* and *ilmenite*, the latter sometimes in deep brown translucent scales.

Apatite is an almost constant accessory, usually in little prisms with the characteristic cross-jointing[4], though in some of the nepheline-dolerites, *etc.*, it builds larger and stouter crystals. A pale violet or blue tint, with evident dichroism, is not infrequent. Some of the leucite- and nepheline-lavas have *melanite*-garnet, brown in slices and always isotropic. A very common accessory in certain leucite- and nepheline-rocks is *perofskite*, in minute octahedra, showing in high relief in consequence of their refractive index[5].

[1] Cohen (3), pl. XLII, figs. 1, 2.
[2] *Ibid.* pl. II, fig. 4; XVIII, fig. 4.
[3] *Ibid.* pl. IV, fig. 4.
[4] *Ibid.* pl. XLVII, fig. 1.
[5] *Ibid.* pl. III, fig. 1.

Leading types. Our illustrations must be drawn wholly from extra-British sources, since no examples of any of the types here considered are known in this country.

It should be noticed that the several types to be distinguished are not always sharply marked off from one another. This is especially the case with the felspar-bearing members, the tephrites and the basanites having in great measure the same general characteristics, except for the not very considerable proportion of olivine in the latter. The differences between the leucitites and nephelinites on the one hand and the leucite- and nepheline-basalts on the other are, however, more marked, the olivine-bearing types being notably richer in the ferro-magnesian constituent (augite) and in iron-ores.

Of *leucite-tephrite* the best-known examples come from the volcanic districts of Italy[1], and we may take as a type that of Tavolato[2] near Rome. It is remarkable for an abundance of blue haüyne. There are two generations of leucite, both showing twin-lamellation. A greenish-brown ægirine occurs as well as augite. Both lath-shaped plagioclase and sanidine are found, the latter sometimes occurring as an interstitial matrix to the other minerals, though in other examples there is some glassy residue. The rock also contains grains of melanite.

The lavas of Vesuvius[3] stand between leucite-tephrite and *leucite-basanite*, olivine being, as a rule, not very abundant. The conspicuous phenocrysts are of leucite (with inclusions of brown glass and augite-microlites), plagioclase (often in radiating groups of crystals), augite, and usually olivine (fig. 58), and the same minerals, except the last, recur as constituents of the ground-mass. Magnetite and apatite are always present, and in some cases biotite is plentiful. Nepheline, sanidine, and brown hornblende are rarer, and sodalite is confined to

[1] Washington, *Journ. Geol.* (1896) iv, 561–564 (Bolsena); *ibid.* (1897) v, 42, 43 (L. Bracciano), and 246–248 (Rocca Monfina).

[2] Cohen (3), pl. XXVII, fig. 2.

[3] *Ibid.* pl. II, fig. 4; XIV, fig. 1; XVII, fig. 2; XIX, fig. 1; XXXIX, fig. 4; Fouqué and Lévy, pl. XLIX, fig 1; Haughton and Hull, *Tr. Roy. Ir. Acad.* (1875) xxvi, pl. II.

crevices, where it seems to have been formed after the consolidation of the rock. The ground-mass is usually holocrystalline or with only a little brownish or yellowish glass, but there are vitreous[1] and pumiceous modifications.

The rock described by Hague[2] from the Absaroka range in Wyoming resembles a leucite-basanite, but has affinities with the leucitophyres. Olivine and augite are enclosed in a ground-mass essentially of leucite and sanidine, plagioclase being only scantily represented. Magnetite, apatite, and a little mica are present, and there may be a very small proportion of glassy base.

Nepheline-tephrites have been described by Zirkel[3] from the Kawsoh Mts in Nevada. These have sanidine predominating over the plagioclase: augite crystals and needles, magnetite, and interstitial nepheline are the other constituents.

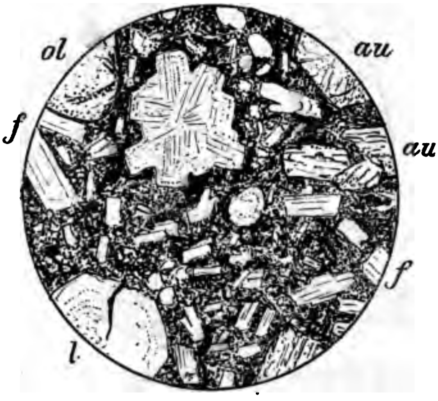

FIG. 58. LEUCITE-BASANITE, VESUVIUS; × 20.

This shows leucite (*l*) and crystals or groups of felspar (*f*), both with zones of inclusions, augite (*au*), olivine (*ol*), magnetite, and a little isotropic residue [845].

[1] Fouqué and Lévy, pl. XLI, fig. 2; Cohen (3), pl. III, fig. 2.

[2] *A. J. S.* (1889) xxxviii, 45. This rock falls under the leucite-absarokite of Iddings, *Journ. Geol.* (1895) iii, 939.

[3] *Micro. Petrogr. Fortieth Parallel* (1876) 255, 256.

From the Elkhead Mts and other localities in Colorado the same writer[1] notes examples of *nepheline-basanite*. One type, of coarse texture, has large crystals of olivine, idiomorphic zoned augite, plagioclase, and interstitial nepheline. Magnetite is plentiful, and biotite is often present. A nepheline-basanite from Southern Texas[2], on the other hand, is of a type poor in olivine, carrying brown hornblende among the phenocrysts and sanidine in the ground-mass. From the western (Trans-Pecos) district of Texas comes a nepheline-tephrite containing abundant green augite, brown hornblende, and biotite in a ground-mass of plagioclase and nepheline[3]. A nepheline-basanite has been described from North Dural in New South Wales[4], and others occur in the Dunedin district of New Zealand[5].

FIG. 59. LEUCITITE, CAPO DI BOVE, NEAR ROME ; × 100.

Small leucites with zonally grouped inclusions are numerous, and augite and magnetite also occur. All these are enclosed by a large crystal of yellowish striated melilite. In other parts of the slide sanidine plays a similar part [G 243].

[1] *Micro. Petrogr. Fortieth Parallel* (1876) 256–258.
[2] Osann, *Journ. Geol.* (1893) i, 344–346.
[3] Osann, *4th Ann. Rep. Geol. Sur. Tex.* (1892) 134.
[4] Card, *Rec. Geol. Sur. N. S. W.* (1903) vii, 237.
[5] Marshall, *Q. J. G. S.* (1906) lxii, 409, 410.

Good examples of the type *leucitite* come from the Alban Hills, near Rome (Capo di Bove[1], *etc.*). They are non-porphyritic rocks, very rich in leucite and relatively poor in augite. Other constituents are brown biotite, yellow striated melilite, and clear sanidine, all of which occur in crystal-plates enclosing the leucite and augite in pœcilitic or ophitic fashion (fig. 59). Other leucitites come from neighbouring volcanic districts[2].

The rock first described by Zirkel[3] from the Leucite Hills, Wyoming, is even richer in leucite. In addition to this mineral, it contains a pale biotite, scattered needles of green augite, apatite, and a small quantity of magnetite. Kemp[4] has shown, however, that the lavas forming these hills present considerable variation. In particular the leucite gives place to sanidine in various proportions, affording transitions to leucitophyre. From the variety containing leucite to the exclusion of sanidine (Wyoming type) Cross[5] has separated that with abundant sanidine (Orenda type); and it appears that the latter is the prevalent type, the leucitite proper being only a special variety[6]. Cross has also described another rock which consists of diopside and yellow mica with a glassy base which has the composition of leucite (Madupa type)[7].

A leucitite from the Bear-paw Mts of Montana[8] contains phenocrysts of augite and leucite in a ground-mass consisting essentially of minute skeleton leucites with very little interstitial glass.

The *leucite-basalts* differ from the leucitites, not only in containing olivine, but also in their greater richness in the ferro-magnesian minerals in general.

[1] Cohen (3), pl. II, fig. 2, and pl. XXVIII, fig. 3; Fouqué and Lévy, pl. L, fig. 1. See also fig. 2 of latter for a type richer in augite, from Frascati.

[2] Washington, *Journ. Geol.* (1896) iv, 556–558 (Bolsena); *ibid.* (1897) v, 41, 42 (L. Bracciano), 46, 47 (Cerveteri), 245 (Rocca Monfina).

[3] *Micro. Petrogr. Fortieth Parallel*, 260, 261; pl. V, fig. 4; I, figs. 21–23.

[4] *Bull. G. S. Amer.* (1897) viii, 175–180.

[5] *A. J. S.* (1897) iv, 120–133, and in Diller, 186–191.

[6] Kemp and Knight, *B. G. S. A.* (1903) xiv, 305–336, pl. 42.

[7] *Ibid.* 331, pl. 46.

[8] Weed and Pirsson, *A. J. S.* (1896) ii, 144–148, with figures.

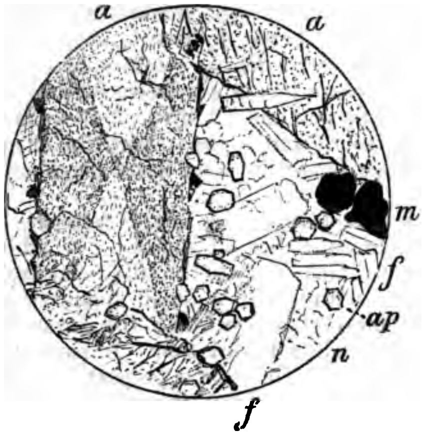

FIG. 60. NEPHELINITE (NEPHELINE-DOLERITE), LÖBAUER BERG, SAXONY; × 20.

The minerals shown are nepheline (*n*), some felspar (*f*), purplish-brown augite (*a*) with hour-glass structure, magnetite (*m*), and apatite (*ap*), the rock being holocrystalline. The coming in of felspar marks a transition to the tephrite type [G 220].

Weed and Pirsson[1] have described specimens from the Bear-paw Mts, Montana. Here the leucites, up to $\frac{1}{50}$ inch in diameter, are turbid from alteration. The other phenocrysts are olivine and pale brown zoned augite, and these minerals occur abundantly in a ground-mass of magnetite grains, augite microlites, and what appears to be a colourless glass.

Leucite-basalt has been described from localities in New South Wales[2]. The abundant olivine has a somewhat peculiar character. This, with leucite and sometimes ragged flakes of yellow mica, belongs to the earlier stage of consolidation, while the ground-mass of the rock is a finely-

[1] *A. J. S.* (1896) i, 288–290.

[2] Judd, *M. M.* (1887) vii, 194, 195; Edgeworth David and Anderson, *Rec. Geol. Sur. N. S. W.* (1890) i, 159-162, pl. XXVIII; Curran, *Journ. Roy. Soc. N. S. W.* (1891) xxv, 210, 211.

crystalline aggregate of leucite, yellowish-green augite, and magnetite, with occasionally a little glass (fig. 61, *A*).

The rocks rich in nepheline are almost always holocrystalline. A well-marked type is the doleritic ***nephelinite*** or nepheline-dolerite of Löbau in Saxony, a rock of comparatively coarse texture, with abundant nepheline. The augite is of a purple-brown pleochroic variety, with hour-glass or other zonary growth, and often idiomorphic (fig. 60). Locally the structure of the rock may become intersertal or, again, micrographic[1]. Besides the abundant nepheline, subordinate sanidine may occur, and more rarely a plagioclase. The common iron-ore is a titaniferous magnetite, and apatite needles occur abundantly. In the otherwise similar type of Meiches, in the Vogelsberg (Hesse), leucite, in irregular grains crowded with apatite needles, becomes a prominent constituent. Both rocks

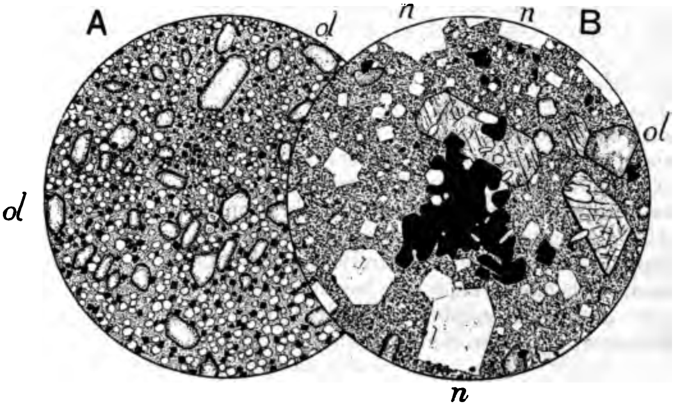

FIG. 61. × 20.

A. Leucite-Basalt, El Capitan, New South Wales: composed of olivine (*ol*), largely serpentinized, leucite, magnetite, and augite [4303].

B. Nepheline-Basalt, Fogo, Cape Verd Isles: showing olivine, augite, nepheline, and magnetite in a fine ground-mass of smaller nepheline and augite granules [2301].

[1] Cohen (3), pl. xxxiv, fig. 2.

show transitions to nepheline-basalt, of finer texture, with less nepheline and with abundant phenocrysts of olivine. The same is true of another well-known nephelinite, that of Katzenbuckel in the Odenwald (Baden). A typical nepheline-dolerite has been recorded from Shannon Tier in Tasmania[1].

The *nepheline-basalts*, much more widely distributed than nephelinites, show less variety of character. They are typically holocrystalline rocks composed of nepheline, augite, and olivine, with some magnetite and apatite. Some contain biotite in addition to augite, and haüyne may accompany the nepheline[2]. Such rocks are known in Hesse and Thuringia, the Eifel, many parts of Saxony, Bohemia, the Cape Verd and Canary Islands (fig. 61, *B*), Brazil[3], *etc.* The chief variation depends upon the coming in of melilite in addition to nepheline, while leucite is a less common accessory.

Several American examples have been described. From the Cripple Creek district, Colorado, Cross[4] notes a dyke very rich in olivine, augite, and magnetite, with a subordinate colourless base, chiefly of nepheline. From southern Texas Osann[5] describes a rock in which large olivines are abundant, with magnetite and small octahedra and grains of brownish-violet perofskite. The holocrystalline ground-mass consists of abundant augite-prisms, tabular crystals of faint yellow melilite with characteristic cross-fibration and 'peg-structure' (Ger. Pflockstructur), and aggregates of shapeless grains of nepheline. Felspar is entirely wanting. This rock is intermediate between nepheline-basalt and melilite-basalt. Card[6] has described nepheline-basalts from the Peak, Upper Burrogorang, New South Wales.

[1] Twelvetrees and Petterd, *Papers and Proc. R. S. Tas.* for 1898–9 (1900) 60–64.

[2] Fouqué and Lévy, pl. XLIX, fig. 2.

[3] G. H. Williams, *A. J. S.* (1889) xxxvii, 186, 187 (Fernando de Noronha).

[4] 16*th Ann. Rep. U. S. G. S.* part II (1895), 49, 50.

[5] *Journ. Geol.* (1893) i, 341–343.

[6] *Rec. Geol. Sur. N. S. W.* (1903) vii, 236.

D. SEDIMENTARY ROCKS.

UNDER the head of sedimentary rocks we shall include the stratified deposits formed for the most part, though not exclusively, under water by the accumulation of detritus and of fragmental material of volcanic origin, by organic agency, and by chemical action or the evaporation of saline solutions. The last clause includes the secondary cementing material of many fragmental rocks, as well as the less common deposits of rock-salt, *etc.*, which do not demand special notice.

The rocks exhibit great variety of composition and characters, and in the nature of the case do not admit of any very strict petrological classification. They will be treated here under four groups: the coarser detrital deposits (*arenaceous*), the finer detrital deposits (*argillaceous*), the rocks consisting essentially of carbonate of lime (*calcareous*), and the fragmental volcanic rocks (*pyroclastic* of some authors). In all, with the exception of some of the calcareous rocks, a fragmental or '*clastic*' structure is essentially present: this, with the bedded occurrence, may be taken as characteristic of the whole.

CHAPTER XVI.

ARENACEOUS ROCKS.

THE arenaceous rocks are typical fragmental ('clastic') accumulations, consisting of grains of one or more materials mechanically derived, to which may be added interstitial matter deposited in place. There is thus a distinction between original or 'allothigenous' constituents, derived from a distance, and secondary or 'authigenous' constituents, formed after the accumulation of the grains. The fragmental nature of the rocks is usually evident to the eye, and the conditions of deposition in water may be indicated by an appearance of lamination, but this is rarely so well marked as in some argillaceous rocks.

The name *sand* (Fr. sable) is reserved for incoherent deposits : when compacted by some cementing medium, they become *sandstone* or *grit*. These last two words are often used synonymously, though different writers have employed them to mark various distinctions. If a distinction be made, it is perhaps best to name the round-grained rocks sandstones, and those with angular grains grits. Such epithets as felspathic and calcareous are used to describe the nature sometimes of the grains, sometimes of the cement : they usually need no explanation. The old term *greywacke* (Ger. Grauwacke) has been revived for a complex rock with grains of quartz, felspar, and other minerals and rocks united by a cement usually siliceous. An *arkose* is a deposit derived directly from the destruction of granite or gneiss, and containing abundant felspar. A *quartzite* (of the type belonging here) is a rock consisting of grains chiefly of quartz with a quartz cement.

Derived grains[1]. Since most sands are derived directly or indirectly (*i.e.* through the medium of earlier sedimentary deposits) from the waste of igneous or crystalline rocks, the *most usual minerals* in sand-grains are those which figure largely in the composition of large areas of rock, such as granites, gneisses, and crystalline schists. But chemical processes tend to make a selection among these constituents; for the material is commonly affected by partial decomposition, either prior to the disintegration of the parent rock-masses, during transport, or subsequently to the accumulation of the clastic deposit. So the commonest constituents of sands are those abundant rock-forming minerals which are least prone to chemical changes, such as quartz and white mica. Felspars, augite, hornblende, and dark micas may occur plentifully in particular deposits, but are less characteristic of sands in general, while unstable minerals like olivine rarely occur among detrital material. Certain accessories, such as zircon and rutile, are widely distributed in sands, but only in small quantity. Others may be abundant locally, just as the modern sands on our coasts are found in particular localities to be rich in garnet, or flint, or tourmaline, or ilmenite (menaccanite)[2]. The admixture of few or many constituents depends on the extent and geological diversity of the drainage-area from which the material was derived. River- and lake-sands usually show less variety than those of marine origin[3].

Some coarse-grained deposits contain composite *rock-fragments, e.g.*, a piece consisting of quartz and felspar with the relations characteristic of granite. Other sandstones have numerous fragments of lava. Recent deposits near the volcanic

[1] For much information on sand-grains see Sorby, *Presid. Address, Q. J. G. S.* (1880) xxxvi, *Proc.* pp. 47–65; also *Anniv. Address Micro. Soc.* (1877) *Monthly Micro. Journ.*

[2] The heavier accessories may be separated from loose sands by levigation in water, as described by Mr Dick, *A New Form of Polarising Microscope* (1890) 41–45. A useful adjunct for this purpose is the 'batêa' or Brazilian miner's pan: see Derby, *Proc. Rochester Acad. Sci.* (1891) i, 198–206. For a dry method, see Carus-Wilson, *Nature* (1889) xxxix, 591. For an example of a systematic investigation, see Retgers on the dune-sands of Holland, *M. M.* (1895) xi, 113, 114 (*Abstr.*).

[3] See Julien and Bolton, *Proc. Amer. Assoc.* (1884) 413–416.

islands of the Pacific sometimes consist wholly of rolled fragments of lava, pieces of decomposing volcanic glass (palagonite), small chips of pumice, *etc.* By admixture of material of *directly* volcanic origin these volcanic sands graduate into tuffs.

The accumulations composed mainly or entirely of organic fragments (shell-sands, coral-sands, *etc.*) are more conveniently placed with the limestones.

The *form and superficial characters* of sand-grains, best studied by mounting the material dry or in water, depend upon the properties of the individual minerals and their mode of occurrence in the parent-rocks; upon the effects of attrition during transport; and sometimes upon crystalline growth subsequent to the accumulation of the deposit. Grains of felspar, hornblende, *etc.*, usually have their boundaries partly determined by the cleavages of the minerals; mica tends to form flat flakes or scales; minerals like zircon and anatase, which in the parent-rock built small well-formed individuals, often preserve their form intact. They are probably released in some cases by the destruction in the sand itself of an enclosing mineral, such as biotite. Quartz breaks into fragments of irregularly angular outline. If originally of interstitial occurrence (*e.g.* in a granite) it partly retains its highly irregular contour, and the minor irregularities produce a rather opaque appearance on the surface. Quartz-grains from a fine mica-schist, on the other hand, tend to flaky and lenticular shapes.

The degree of *rounding* produced by attrition during transport depends on the hardness of the mineral, but also on the nature and duration of the mechanical agencies involved. Large grains are often more rounded than small (fig. 62). Marine sands are in general more round-grained than those of rivers and lakes, while wind-borne sands, such as those of deserts, are still more rounded by friction[1]. Only in these last are the smallest grains ever found to be well rounded.

[1] For illustrations see *Tr. Edin. G. S.* (1897) vii, pl. XI, fig. 1; XIX, figs. 2, 3; Tenison-Woods, *Journ. Roy. Soc. N. S. W.* (1888) xxii, pl. XXII, XXIII (Sahara and N. Australia).

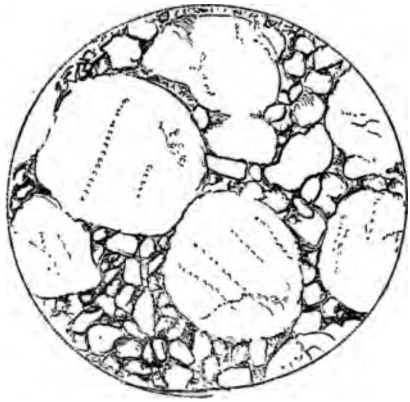

FIG. 62. 'TOP GRIT' OR UPPERMOST BED OF THE CAMBRIAN QUARTZITE SERIES, NEAR INCHNADAMPH, SUTHERLAND; × 20: showing small angular quartz-grains occupying the interstices between the larger rounded ones [1665].

It is usually possible to form some opinion as to the source or *sources of the derived material* of a sand. The minerals identified give a clue to the parent-rock or rocks, and special features in the minerals may also afford information. Thus the existence of fluid-, glass-, or other cavities in crystal-fragments, the presence of rutile-needles in quartz-grains, *etc.*, may tell us whether the minerals in question originally formed part of a plutonic, a volcanic, or a metamorphic rock, or of several different rocks[1]. Too much stress must not be laid on the rounding of grains as indicating the distance of their source. Long-continued drifting to and fro within a limited area may cause more attrition than a thousand miles of travel in one direction: further, friction is much more effective under subaërial than under subaqueous conditions. Again, sand-grains have often been furnished ready-made by the destruction of older arenaceous deposits.

[1] See, *e.g.*, Mackie's investigation of the Old Red Sandstone of Eastern Moray, *Tr. Edin. G. S.* (1897) vii, 148–172.

The *coarseness or fineness* of sandstones may vary considerably. The sifting action of running water tends to collect in one place grains of roughly equal dimensions, but some sandstones contain grains of two very different sizes, the smaller occupying the interspaces between the larger (fig. 62). A very common size for the grains of quartz and felspar in many sandstones is from ·01 to ·03 inch[1].

Authigenous constituents. In addition to the clastic grains, sandstones and grits contain material deposited upon the surfaces of the grains, or filling in partially or wholly the interstices between them, and thus serving to bind them into a coherent rock. Whether formed by the recrystallization of calcareous or other matter laid down with the detritus, by the redeposition of material dissolved from the grains themselves, or by the introduction in solution of some extraneous substance, this cement must be regarded as formed in place, and its accumulation constitutes a new chapter in the history of the rock. The cementing medium itself is usually calcareous, ferruginous, siliceous, or some mixture of these.

The *calcareous cement* has probably been in most cases deposited in the form of mud, comminuted shells, *etc.*, with the original grains, but it becomes effective as a binding material only after some amount of solution and redeposition, which commonly gives it a more or less evident crystalline texture. Exceptionally a crystalline growth of calcite may enclose grains in ophitic or pœcilitic fashion, as in the Fontainebleau Sandstone of the Paris Miocene[2], but usually the calcareous cement is strictly interstitial, and it does not always fully occupy the interspaces between the grains. In rare cases other salts, such as gypsum and barytes, may serve as a cement.

Many sandstones are cemented by *ferruginous* matter or a mixture of ferruginous and calcareous. The red oxide and the brown hydrated oxide of iron occur in this way. Frequently the oxide forms a thin coating or pellicle round each grain of

[1] See Bonney, *Rep. Brit. Ass.* for 1886, p. 601, and *Nature* (1886) xxxiv, 442.

[2] A similar rock occurs at Rock Lily, near Narrabeen, N. S. W.; see David, *Journ. Roy. Soc. N. S. W.* (1894) xxii, 406, 407.

sand. This pellicle can be removed by acid, leaving the grains colourless.

The clayey material (kaolin, very fine mica, *etc.*), which occurs interstitially in some sandstones, is probably to a great extent authigenous, representing the decomposition of felspar grains, *etc.* Similarly a chloritic mineral is not uncommon, and may be derived from the destruction in place of such minerals as hornblende and biotite.

In the tougher sandstones and grits the cementing matter is in the main *siliceous*. When the grains are angular and of various sizes, the interspaces may be very small, and the interstitial silica, concealed by the grains and perhaps by kaolin dust or iron-staining, may be difficult to observe. In more or less porous rocks, the little cementing matter required may be provided by some slight solution of the quartz-grains themselves at the points where they press on one another, as suggested by Mr Wethered for the sandstones of the Bristol coalfield.

When spaces have existed between the original grains, it is usually seen that the siliceous cement has been deposited in

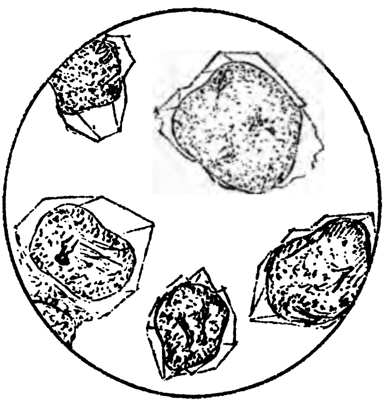

FIG. 63. QUARTZ-GRAINS FROM PENRITH SANDSTONE, PENRITH BEACON, CUMBERLAND; × 20:

showing a secondary outgrowth of quartz with crystal-faces [1920].

crystalline continuity with the original quartz as a *new outgrowth of the clastic grains.* The secondary enlargement of the grains is verified by the new material extinguishing simultaneously with the old between crossed nicols. Again, many sandstones which have not been compacted into hard rocks exhibit a similar new growth on the surfaces of the grains; and in this case (fig. 63) the added material often shows good crystal faces[1] ('crystallized sand'). The enlargement is commonly clearer than the nucleus, and the division between them is marked by a line of dusty inclusions or by a thin partial coating of some deposit older than the outgrowth. Though characteristic of quartz, a similar outgrowth is occasionally

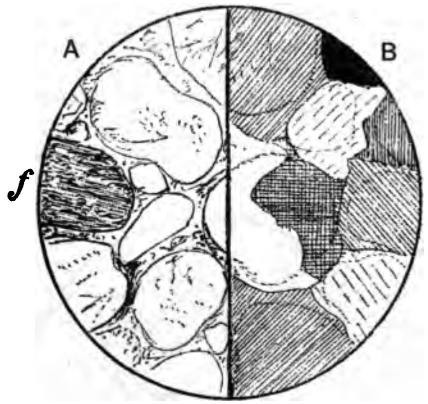

FIG. 64. QUARTZITE, STIPERSTONES, SHROPSHIRE; × 50:

A in natural light, *B* between crossed nicols. The grains are of rolled quartz with an occasional turbid felspar (*f*), and the interspaces are filled by a secondary outgrowth of quartz from the grains. The shading is diagrammatic, to indicate different interference-tints. A composite grain in the centre shows outgrowths from both portions [224].

[1] Sorby (*Address cit. supra*, 62–64). For figures see R. D. Irving, *5th Ann. Rep. U. S. Geol. Sur.* (1885) pl. xxx; Irving and Van Hise, *Bull. No.* 8 *U. S. Geol. Sur.* (1884) pl. II; Phillips, *Q. J. G. S.* (1881) xxxvii, pl. II.

found on fragments of felspar[1] and hornblende[2]. In less frequent examples new-formed quartz has a radial arrangement about original grains, or is oriented independently. Again, a cement of cryptocrystalline or chalcedonic silica is known in some rocks.

When a deposit originally a quartz-sand becomes completely compacted by an interstitial cement of secondary quartz, the result is a *quartzite* of the ordinary type. Such rocks often consist wholly, or almost wholly, of quartz, but in a thin slice the distinction between the derived grains and the interstitial cement comes out clearly. Usually the new quartz is a crystalline outgrowth from the grains, the space between two grains being occupied by quartz, of which part is in continuity with one grain, part with the other. Between crossed nicols the slice therefore assumes the appearance of an irregular mosaic[3] (fig. 64).

Some British examples[4]. The forms and general characters of sand-grains may be studied in modern deposits[5] and in the sands, not yet compacted into sandstone, of the later geological formations. Among the materials quartz, as a rule, largely predominates, but the sands of our modern coasts are locally rich in other minerals, such as flint, garnet, tourmaline, magnetite, ilmenite (Cornwall)[6], silicified wood (Eigg), *etc.* Most sands contain a small proportion of certain heavy minerals, which can be separated by special methods. In the fine-grained Bagshot Sands of Hampstead Heath and

[1] Irving, *l. c.*, pp. 237–241, and 44–47.

[2] Van Hise, *A. J. S.* (1885) xxx, 232–235.

[3] For coloured figures see Teall, pl. XLV, fig. 2: XLVI, fig. 1; Irving (*cit. supra*), pl. XXXI; Irving and Van Hise, *On Secondary Enlargements of Mineral Fragments* (1884), *Bull. No.* 8 *U. S. Geol. Sur.*, pl. III–VI.

[4] Interesting information concerning British arenaceous rocks is contained in Sorby's *Presidential Address*, quoted above, and earlier papers (*Proc. Yorks. Geol. and Pol. Soc.*, *etc.*). See also J. A. Phillips, *Q. J. G. S.* (1881) xxxvii, 6–27; Bonney, *Nature* (1886) xxxiv, 442–451, and *Rep. Brit. Ass.* for 1886, 601–621.

[5] For an account of the sands and other deposits now forming in the Irish Sea see Herdman, *Rep. Brit. Ass.* for 1894, 328–339, and *Pr. Liverp. G. S.* (1895) vii, 171–182; Herdman and Lomas, *ibid.* (1898) viii, 205–232.

[6] A titaniferous iron-sand occurs also at Porth-dinlleyn, Caernarvonshire; see Cope, *Pr. Liverp. Geol. Soc.* (1902) ix, 208–219.

of High Beech in Essex Mr Dick[1] found up to 4 per cent. of dense minerals, including magnetic iron-ore, zircon, rutile, and tourmaline. Many sands contain small quantities of these and other special minerals (garnet, cyanite, anatase, *etc.*). The basal bed of the Thanet Sands contains 20 per cent. of flint in sharply angular chips, with quartz, glauconite, and numerous other minerals[2]. The flint is of course derived from the Chalk.

The form of quartz-grains depends in great measure upon their source, whether directly from crystalline rocks or from older sandstones or grits. Thus the Glacial sands of the Yorkshire coast, which must come chiefly from crystalline rocks, have sharply angular shapes, and the grains on the modern beaches of that coast, most of which are doubtless washed out of the Glacial accumulations, are scarcely more abraded. On the other hand, modern sands on the south-east coast of England, derived very largely from older arenaceous deposits, have a considerable proportion of rounded grains. On the north-west coast both Glacial and modern sands often contain extremely rounded grains, explained as being derived from the 'millet-seed' sandstones of the Trias, but these are mixed with angular quartz in various proportions. The grains of the sand-dunes on our coasts are much less rounded than those of desert sands.

The Mesozoic formations afford numerous examples of calcareous and ferruginous cements; less frequently of siliceous, although this also is sometimes found, and indeed, the 'Moor Grit,' a conspicuous coarse-grained bed in the Lower Oolites of the Yorkshire moors, is rather a quartzite than a grit[3]. In some Jurassic strata a calcareous and a siliceous cement are associated in the same rock (fig. 65, *A*). The Kellaways rock has usually a ferruginous cement. The same is true of many of the Neocomian sandstones (fig. 65, *B*), while in others the cementing medium is of granular calcite, which may be iron-stained. Occasionally the calcite builds large plates enclosing

[1] *Nature* (1887) xxxvi, 91, 92; Teall, pl. XLIV; *cf.* Fouqué and Lévy, pl. IV.

[2] Miss Gardiner, *Q. J. G. S.* (1888) xliv, 755–760.

[3] This is often true also of the well known 'sarsen stones' or 'greywethers,' of Wiltshire, Dorset, *etc.*; *cf.* Judd, *G. M.* 1901, 1, 2.

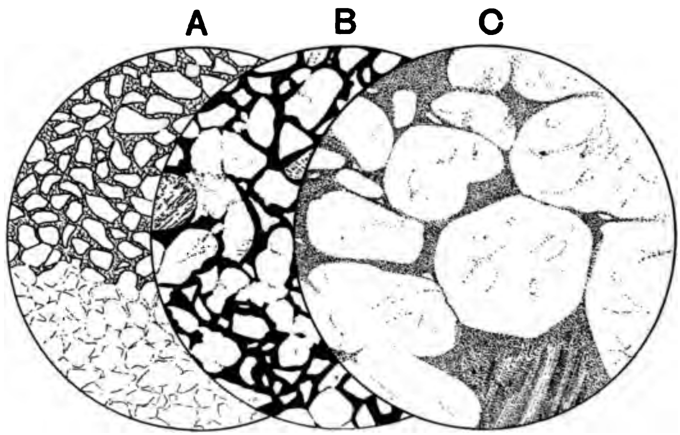

FIG. 65. BRITISH SANDSTONES; × 20.

A. Fine-grained Sandstone, Oolitic series, Isle of Eigg. The cement is calcareous in the upper part of the field and siliceous in the lower [4280].

B. Medium-grained Sandstone, Neocomian, Shotover Hill, Oxford: with ferruginous cement [2192].

C. Coarse Sandstone, near Llandeiniolen, Caernarvonshire. The interstitial cement is provided largely by the decomposition of grains of felspar (see lower part of field), the resulting clayey matter being squeezed between the quartz-grains and strengthened by secondary silica [4161].

many of the partly rolled quartz-grains (Spilsby in Lincolnshire, Copt Point near Folkestone). Many of these rocks have little grains of bright green glauconite with various rounded shapes, explained as casts of foraminifera. Another feature is the occurrence of little round oolitic grains of dark brown iron-ore ('carstone' of Hunstanton, and Roslyn Hill, Ely). These grains have a concentric shell structure, and, when dissolved in acid, leave a siliceous skeleton. Zircon crystals are among the denser constituents[1]. The best British examples of glauconitic sands come from the base of the Cretaceous

[1] Hume, *Q. J. G. S.* (1894) l, 679 (Bargate); *20th Cent. Atlas*, 32 with plate.

in Antrim. The glauconite grains, unusually large and abundant, are all casts of foraminiferal chambers[1]. The glauconitic sands of the Upper Greensand in Wiltshire, Dorset, Devon, and the Isle of Wight are chiefly of coarse quartz-sand with fragments of felspar and mica, but large glauconite grains are abundant. There is often a calcareous cement[2]. Similar glauconitic sandstones of Upper Greensand age are found in the Inner Hebrides, *e.g.* at Carsaig in Mull.

The Upper Palæozoic grits and sandstones of this country often have a cement largely ferruginous or consisting of iron-oxide and quartz. In the Devonian of South Devon are fine-grained sandstones which, with predominant quartz, have little flakes of mica, some felspar, and small granules of tourmaline, indicating the source of the material: the interstitial matter is for the most part ferruginous. Much of the Old Red Sandstone shows the investing pellicle of ferric oxide around each grain.

This latter feature and numerous other points of interest may be studied in many parts of the New Red Sandstones. In particular, quartz-grains with a secondary outgrowth having crystal-faces are common at various horizons of the Keuper and Bunter[3] of Shropshire, Cheshire, *etc.*, and are also exceptionally well exhibited in some coarse-grained beds of the Penrith Sandstone[4] (Penrith Beacon, Cumberland), (fig. 63) In some cases a pellicle of iron-oxide coats the new crystal growth, and must then be long posterior to the date of the strata. Red sandstones are often of quite yielding consistency, even when the interstices are occupied by quartz. This is because of a coating of iron-oxide intervening between the interstitial quartz and the original grain. By treatment with acid, the irregularly shaped patches of interstitial quartz were

[1] Hume, *Q. J. G. S.* (1897) liii, 569–571.

[2] On these and other arenaceous rocks of the Upper Cretaceous see W. Hill in *Mem. Geol. Sur., Cret. Rocks Brit.*, vol. i (1900) chap. xxv.

[3] For descriptions of Triassic sandstones from the Vale of Clwyd, Cheshire, and Lancashire, see Morton, *Geology of Liverpool* (2nd ed. 1891) 129–132; M. Reade, *Pr. Liv. G. S.* (1892) vi, 374–386; Dickson and Holland, *ibid.* (1896) vii, 449–451; Moore, *ibid.* (1898) viii, 241–265; Lomas, *ibid.* 265–267, pl. XIII.

[4] *20th Cent. Atlas*, 36, with plate.

isolated by Mr Phillips from the 'millet-seed' sandstones of the Trias. In these beds the perfectly rounded form of the original grains is attributed to their having been true desert-sands[1]. The Bunter Pebble-bed at Budleigh Salterton and elsewhere includes among its finer materials a considerable variety of the denser minerals[2]; and this seems to be true of the Trias generally in the Midland Counties, anatase being found with other minerals[3].

Many Carboniferous grits have sharply angular grains, and were probably derived directly from crystalline rocks. The coarse-grained Millstone Grit of South Yorkshire[4] has highly irregular quartz-grains poor in fluid-cavities. There is not much fresh felspar, but argillaceous matter between the quartz-grains seems to represent it. The hard 'ganister' has angular quartz-grains which fit so closely together as to obscure the small amount of siliceous cement, and the same is true of the grits of the Bristol coal-field. In some beds in the Coal-Measures numerous flakes of muscovite, lying parallel to the lamination, impart a fissile character to the rocks (Bradford Flags, *etc.*). The spaces between the grains are often obscured by kaolin. Kaolin and relics of reddish orthoclase, with a little mica and sometimes tourmaline, are found in the Millstone Grit of south-west Lancashire[5], which consists mainly of angular quartz-grains of very variable size (·2 to ·005 inch) with crystalline outgrowths not very common. In the Cefn-y-Fedw Sandstone of Denbighshire and Flintshire[6] the grains are angular to rounded, and more often have secondary outgrowths with crystal-faces.

The Lower Palæozoic and older arenaceous rocks are, as a rule, thoroughly compacted, the cement being for the most part siliceous. Mr Phillips found the quartz-cement of various

[1] *Cf.* Mackie on the Reptiliferous Sandstone of Elgin, *Tr. Edin. G. S.* (1897) vii, 166, pl. XIX, fig. 2.

[2] Thomas, *Q. J. G. S.* (1902) lvii, 620–631, pl. XXXI, XXXII.

[3] Scrivener, *M. M.* (1903) xiii, 348–351.

[4] Sorby, *Pr. Yorks. Geol. Pol. Soc.* (1859) iii, 669–675. On the Millstone Grit of the Forest of Dean see Wethered, *Pr. Cottesw. F. N. Club* (1883) viii, 25–27, with plates.

[5] Morton, *Proc. Liverp. G. S.* (1887) v, 280–283.

[6] *Ibid.* 271–279.

Cambrian and Silurian grits (Barmouth, Harlech[1], Aberystwith, Denbighshire) permeated by a moss-like growth of a green chloritic mineral. Both coarse and fine-textured rocks are included. The quartz-grains are angular or partly rounded, and frequently contain needles of rutile and tourmaline: fluid-pores are present in some, absent in others. Some of the grits have plenty of felspars, while pyrites, garnet, and micas are occasionally noted. Specimens of the grits of Skiddaw and of the Isle of Man[2] (Santon) show fragments of slate and lava among the partly rolled quartz and turbid felspars. The Ingleton rock in Yorkshire is a grit containing volcanic material as well as grains and pebbles of quartz, felspars, and various lavas[3]. Volcanic grits of finer texture occur in the upper part of the Ordovician near Shap Wells, Westmorland, and these contain also calcareous matter.

The older sandstones of the Bangor and Caernarvon district and of parts of Anglesey are rather coarse-grained, consisting of well-rounded to subangular quartz with plenty of felspar. The latter mineral is often decomposed, and its clayey decomposition-products wedged in between the quartz-grains, obscuring the siliceous cement (fig. 65, *C*). Some of the rocks, however, have comparatively fresh felspar: a Silurian grit at Drys-lwyn-isaf, south of Parys Mountain, consists almost wholly of grains of oligoclase closely packed together. The prevalent type of the Torridon Sandstone is an example of a coarse sandstone rich in felspar. Besides rolled quartz-grains, often composite, it has others of microcline and fragments of quartzite and pegmatite.

The best examples of *quartzites* in England are those of Hartshill in Warwickshire and the Lickey Hills in Worcestershire, probably of pre-Cambrian age[4], and the Stiperstones in Shropshire (Ordovician)[5]. All these consist essentially of rolled

[1] *Cf.* Greenly, *Tr. Edin. G. S.* (1897) vii, 254–258.

[2] *Cf.* Lamplugh, *Mem. Geol. Sur., Geol. I. Man* (1902) 98, 99.

[3] Tate, *Rep. Brit. Ass.* for 1890, 800.

[4] Teall, pl. XLV, fig. 2, XLVI, fig. 1, and *Pr. Phil. Soc. Birm.* (1882) iii, 194–202; Watts, *Summary of Progress Geol. Sur.* for 1897, 68, and *Pr. Geol. Ass.* (1898) xv, 393, 397; Adye's *Stud. Micropetr.* 5–7, pl. I, fig. 2.

[5] Rutley, *Pr. Liverp. G. S.* (1885) v, 381.

quartz-grains, usually about ·02 to ·03 inch in diameter, with only very subordinate felspar, united by a clear quartz-cement, which is of the nature of a crystalline outgrowth from the grains (fig. 64). A series of quartzites forms the lower part of the Cambrian in the Assynt district, Sutherland. Some beds contain pebbles, and are indeed cemented conglomerates. The uppermost bed ('Top Grit') shows large well-rolled quartz-grains, about ·05 inch in diameter, with smaller subangular grains between them. The remaining space, occupied by the siliceous cement, is obscured by opaque dust (fig. 62). Good quartzites, probably of Cambrian age, occur at Bray Head and Howth near Dublin[1].

[1] Sollas, *Sci. Pr. Roy. Dubl. Soc.* (1892) vii, 174–184, pl. xv; *Pr. Geol. Ass.* (1893) xiii, 91–93, pl. III.

CHAPTER XVII.

ARGILLACEOUS ROCKS.

THE name *clay* is used for argillaceous deposits which still retain enough moisture to be plastic. By the loss of most of their uncombined water and by other more important changes these pass into mudstones, shales, and slates. Of these terms, *mudstone* is correctly used when the rock has no marked fissile character, *shale* when it splits along the original laminæ of deposition, and *slate* when the original lamination has been superseded as a direction of weak cohesion by a new structure (slaty cleavage, Fr. schistosité, Ger. Transversalschieferung). The Continental geologists do not, as a rule, observe this distinction, but include shales and slates under the same name (Fr. schiste, Ger. Schiefer, Norw. skiffer).

Among slates it has been usual to distinguish *clay-slates* (Thonschiefer, lerskiffer), in which the material was supposed to be largely detrital matter without important new formation of minerals, and *phyllites* (Fr. phyllade), in which the rocks are largely or totally reconstituted in place (aided, at least, by pressure). It is now becoming evident, however, that in clay-slates, and even in clays and shales, there has often been a considerable amount of mineral change in place; so that no very sharp line can be drawn between clay-slates and phyllites. The typical glossy phyllites are essentially mica-schists on a small scale, and may be described as micro-crystalline schists. We shall find it convenient to include them here, although we thereby anticipate their place under the head of dynamic metamorphism.

Constituent minerals. Owing to the extremely small dimensions of the elements, it is usually a matter of great difficulty to identify with certainty all the constituents of clays, shales, or slates. Speaking generally, these constituents include some of derived or detrital origin (allothigenous), which were either primary minerals or decomposition-products in the parent rock-masses, and others of secondary origin, formed in place (authigenous). As regards the latter, doubt may exist in particular cases as to how far the secondary recombinations have been induced by pressure (dynamic metamorphism). In many fine-grained slates no constituents are seen which can be set down with confidence as purely detrital. In all cases very thin sections and high magnifying powers must be used. Some of the denser accessory minerals may be isolated from powder by heavy solutions, or merely by washing[1].

The detrital elements may include granules of *quartz*, and less frequently of *felspars*, and scales of *mica*, with minute crystals of such accessories as *zircon*. The little flakes of biotite show more or less decomposition: Mr Hutchings finds that they give rise, not to chlorite, but to *epidote* in minute superposed tablets of light yellow colour. The iron-oxides separate out as *limonite*. *Carbonates* may occur in varying proportion. Many argillaceous rocks contain a considerable quantity of *carbonaceous matter*, finely granular and for the most part opaque: slices may be bleached by incineration on platinum foil. The *pyrites* which occur in many slates, sometimes in relatively large crystals, is of secondary origin, and is perhaps due to the reduction of iron-compounds in the presence of organic matter. The *glauconite* of some argillaceous deposits has also been formed in place[2].

The ordinary fine-grained argillaceous rocks consist in considerable part of an exceedingly fine-textured base o paste, very difficult to resolve, in which any truly detrita

[1] *Cf.* Teall, *M. M.* (1887) vii, 201–204. For a method of studying fine incoherent sediments, see Hutchings on Sediments dredged from the English Lakes, *G. M.* 1894, 300–303.

[2] See W. Hill on the micro-structure and mineral ingredients of the Gault, *Mem. Geol. Sur.*, *Cret. Rocks Brit.*, vol. i (1900) chap. xxiv.

elements or their evident alteration-products are embedded. The nature of this paste has not yet been made out in any large number of cases. It was formerly regarded as consisting essentially of hydrated silicate of alumina (kaolin), *etc.* Careful studies of various clays, shales, and slates lead, however, to the conclusion that the material is to a great extent a very finely divided *micaceous substance* of secondary origin; and this is confirmed by chemical analyses of the rocks, which often show a considerable content of alkalies. According to Mr Hutchings[1], this main constituent of the fine-grained base is in ordinary clays and shales an impure, pale, greenish-yellow mica; while in slates, where crystalline reconstruction is more advanced, it has given place to a mixture of pure muscovite and a chlorite-mineral, the two often in very intimate association. In rocks not completely regenerated there may be observed in addition much indeterminable finely granular matter, which may be conjectured to represent the finest powder of quartz, felspar, *etc.*, and perhaps *kaolin* or other products. A highly characteristic feature of the paste is the presence of an enormous number of minute needles of *rutile* ('clay-slate-needles')[2]. On account of their very small breadth and very high refractive index, the needles often appear as opaque lines, but the larger ones may be transparent. The rutile is generally regarded as of secondary origin, being produced in place in association with the mica, *etc.*, the titanic acid being furnished by derived biotite. Since the changes which gave rise to these secondary products have operated in clays as well as in slates, they cannot be held to imply any advanced dynamic metamorphism, but they may still be favoured by pressure.

Many slates seem to show by their chemical composition the presence of secondary free silica (in addition to any evident detrital quartz which they may contain). This is sometimes seen as a *quartz-cement*, tending to form little veins and

[1] *G. M.* 1896, 312, 313. This author points out the advantages of cutting slices from a specimen previously ignited to redness. The resulting dehydration causes the chloritic substance to become more opaque, or assume a deeper colour, while impure mica is less affected, and the pure muscovite unchanged.

[2] *Cf.* Teall, *M. M.* (1887) vii, 201–204; Cohen (3) pl. III, fig. 4.

patches; in other cases *opal* has been supposed to occur, and indeed amorphous silica may be dissolved out by caustic potash.

In some rocks, especially the Glacial tills, we must suppose that a large part of even the most impalpable material is of detrital origin. Thus in the tills of the Boston basin, Massachusetts, Crosby[1] found that about four-fifths of the finest grade of material was not what is commonly understood by clay, but what he terms 'rock-flour,' *i.e.* the most minute particles of pulverised quartz and other rock-forming minerals, not chemically decomposed.

Structures. Argillaceous rocks in general have a parallel arrangement of their constituent elements which is usually sufficiently marked to impart a fissile character to the mass. Slices parallel and perpendicular to the direction of fissile structure should be compared. In shales a large proportion of the minute constituent elements lie with their flat faces or long axes parallel to the layers of deposition. In true slates, *i.e.* rocks with a superinduced *cleavage-structure*, they have taken up a new direction along planes (cleavage-planes) perpendicular to the maximum compression by which the rock has been affected.

The effect of this compression, accompanied by a certain partially compensating expansion along the cleavage-planes, is well seen in the deformation of concretionary spots of colour, *etc.* A spherical spot becomes distorted into an ellipsoid. A hard unyielding body, such as a crystal of pyrites or magnetite embedded in the rock, gives rise to curious phenomena. The matrix flows past the crystal, leaving a roughly eye-shaped space[2]. Such crystals have in many cases been originally coated with an envelope of chlorite, which adheres to the matrix and is torn away from the crystal. The intervening space is subsequently filled by infiltration with crystalline quartz (fig. 66, *A*).

Various structures, of frequent though local occurrence in

[1] *Proc. Bost. Nat. Hist. Soc.* (1890) xxv, 115–172.
[2] *G. M.* 1889, 396, 397.

fine-grained beds, may be styled '*false' and incipient cleavages*[1]. They consist sometimes in a parallel system of microscopic faults, sometimes in a regular system of minute folds. These

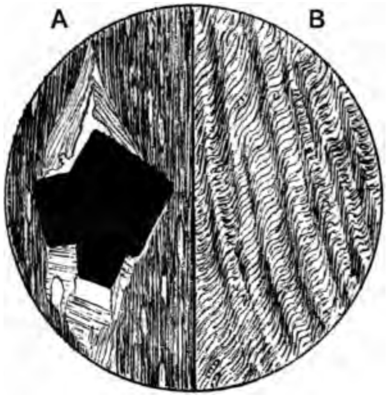

FIG. 66.

A. Slate with crystal of pyrites, Penrhyn, near Bangor; × 5. The crystal is surrounded by an 'eye' of chlorite and quartz, as described. The mass of the slate contains little light spots, which have been deformed into an elliptic shape [501].

B. False cleavage in Skiddaw Slate, Brownber, near Appleby; × 20. The system of minute parallel folds causes a direction of weakness almost equivalent to cleavage [913].

often give a tendency to the rock to split along definite planes, *viz.* the fault-surfaces or the limbs of the folds (fig. 66, *B*). Dr Sorby[2] has shown that such structures may be a step towards a true slaty cleavage. They may also, however, occur as later structures crossing a true cleavage (*e.g.* in various Ardennais slates and phyllites), and they are common in some fine-textured mica-schists. They are often interesting as reproducing on a minute scale the characteristic structures of mountain-ranges, such as the gradual passage of an over-fold into an overthrust fault, the relation of faults to anticlines,

[1] *Rep. Brit. Ass.* for 1885, 836–841. Some writers have used the terms 'close-joints cleavage' (Sorby), 'Ausweichungsclivage' (Heim), and 'strain-slip-cleavage' (Bonney) for structures of this kind.

[2] *Q. J. G. S.* (1880) xxxvi, *Proc.* 72, 73.

etc. A frequent result of shearing movement in finely laminated rocks is the formation of minute oblique folds inclined at about 45° to the lamination: these are pushed over until at about 30° they pass into little faults, and the faults may be further pushed over until they are lost in a general parallel-structure.

Illustrative examples. Before describing some of the commoner types of argillaceous rocks, we may mention one of which very little is known among consolidated strata. It is represented among deposits now forming by the *abyssal red clay* which covers large areas of the ocean-floor below a depth of 2200 fathoms. This deep-sea clay is derived mainly from the destruction of volcanic products by the chemical action of sea-water. Minute fragments of volcanic rocks and minerals are mixed with decomposition-products and with a few siliceous organisms (radiolarians, *etc.*). The brownish-red colour is due to disseminated limonite. Minute crystals of the lime-zeolite phillipsite or christianite are common[1], and manganese-nodules of various sizes occur. There may also be a few corroded tests of foraminifera. Messrs Harrison and Jukes-Browne[2] found that about two-thirds of a typical 'red clay' consists of fine argillaceous matter derived from the destruction of basic pumice or palagonite. The rest is chiefly disintegrated (but not decomposed) acid pumice; while 5 *per cent.* of the clay is matter of organic origin, principally colloid silica. The red and yellow deep-sea clays of the Tertiary in the Barbados have a very similar constitution[3]. Other rocks comparable with the abyssal red clay have been described from the Solomon Islands[4] and from Trinidad[5].

These deep-sea argillaceous deposits have characters which distinguish them from those derived from the waste of land-areas. The particles are of excessive minuteness and markedly angular in shape[6]. The minerals recognizable are those most

[1] See Murray and Renard, 'Challenger' Report, *Deep-Sea Deposits* (1891) pl. XXII.

[2] *Q. J. G. S.* (1895) li, 314–321.

[3] *Cf.* Miss Raisin, *Q. J. G. S.* (1892) xlviii, 180–182.

[4] Guppy, *The Solomon Is., their Geology, etc.* (1887) 81, 82.

[5] Gregory, *Q. J. G. S.* (1892) xlviii, 539.

[6] Murray and Renard, *l. c.*, pl. XXVI, XXVII, figs. 1–4; contrast with fig. 5.

common as constituents of volcanic rocks, such as felspar and augite, rarely quartz; while such minerals as zircon, tourmaline, *etc.*, are absent. Usually a very large proportion of the material consists of angular chips of volcanic glass and elongated fragments derived from the breaking up of pumice with capillary pores.

As another somewhat peculiar type of clay may be mentioned the *china-clay* of Cornwall, which seems to consist essentially of the mineral kaolin[1]. This, in its most recognizable form[2], builds minute colourless scales, sometimes with hexagonal outline, and of such refractive index and birefringence as closely to resemble mica. It appears, however, from Mr Collins's account[3] that these distinct flakes do not form any large part of the finely divided material in the typical occurrences in Cornwall. Besides quartz, mica, and other impurities, tourmaline is found in some rocks composed largely of kaolin, and its production was perhaps connected with the process of 'kaolinization' of felspathic rocks[4]. In addition to the proper china-clays, formed more or less *in sitû*, there are derived clays of similar composition, such as those of Bovey Tracey.

Under certain conditions, not yet made clear, it appears that decaying igneous rocks may be deprived more or less completely of their combined silica, as well as the alkalies and dioxides, the alumina remaining in the form of hydrate, often with ferric hydrate. The *bauxite-clays* of Antrim are of this type, and probably result from the subaërial decomposition of basalt almost in place. Where quartz-bearing rocks have been subjected to this kind of change, quartz-sand remains mixed with the aluminium and iron hydrates. Much of the so-called *laterite*[5] of India and other tropical countries seems to be of this nature.

[1] Some writers apply the name kaolin to the clay itself, and use 'kaolinite' for the mineral. Collins uses the name 'carclazite' for the true kaolin-clay and 'petuntzite' for a less altered variety still retaining relics of undestroyed felspar.

[2] See Dick, *M. M.* (1888) viii, 15–27, pl. III.

[3] *M. M.* (1887) vii, 205–214; Teall, pl. XLIV, fig. 5.

[4] Butler, *M. M.* (1887) vii, 79, 80.

[5] See especially Holland, *G. M.* 1903, 59–69.

We pass on to the consideration of clays and slates of more ordinary constitution, selecting only a few examples which may be regarded as typical[1].

A minute study of typical argillaceous rocks has been made by Mr Hutchings in the case of the *fire-clays* of the Newcastle Coal-measures[2]. The rocks are laminated, and include coarser and finer beds. The material of true detrital origin is most abundant in the coarser beds. It seems to be derived from the destruction of granite, and consists of granules of quartz averaging ·002 to ·003 inch in diameter, granules of felspar, biotite flakes from ·01 inch downward, with the epidotic alteration, less abundant muscovite, and accessory zircon, *etc.* Besides these there is a paste, in which minute scales of secondary mica and needles of rutile are the recognizable elements.

The *shales* of the South Wales coal-field[3] were found to present similar characters, though much obscured by organic pigment. A considerable amount of clastic muscovite, and occasionally biotite, remains with the quartz-granules, and the paste of newly-formed micaceous material has the usual rutile-needles. The Culm-measure shales of Bude in Cornwall[4] are derived from the waste of granite (in part with tourmaline) and crystalline schists. They appear to have undergone more change *in sitû* than the preceding.

The Cambrian *roofing-slates* of North Wales represent a more advanced stage of secondary change, both structural and mineralogical. They possess a strong cleavage-structure, passing indifferently through the layers of original deposition, and the more altered of them have the glossy aspect of fine-textured phyllites, in which little trace of any clastic structure survives. Detrital granules of quartz and felspar may be seen, but biotite is wanting, though little patches of epidote perhaps represent it. "The base and main constituent of all these

[1] For a description of various American clays see Merrill, *Guide to Collections in Applied Geol., Nonmetallic Minerals* (1901) 325–328, pl. 15–17.

[2] *G. M.* 1890, 264–273.

[3] Hutchings, *G. M.* 1896, 310.

[4] McMahon, *G. M.* 1890, 108–113; Hutchings, *ibid.* 188.

slates is a fine-grained mica, mostly lying flat in the plane of cleavage of the rock," and rutile-needles are usually abundant. The red and purple slates contain numerous scales of red micaceous hæmatite, probably representing the limonite of less altered deposits. A number of specimens of slates, Cambrian and Ordovician, from this region have been described by Mr Hutchings[1].

The Devonian slates of Cornwall (Tintagel, *etc.*) are described by the same author[2] as having suffered more alteration (ascribed to dynamic metamorphism) than the Welsh rocks. They have no clastic quartz, felspar, or biotite, and indeed some very small zircons seem to be the only derived constituents left unaltered. The main mass of the rock is of fine sericitic mica, the majority of the minute flakes being parallel to the cleavage of the rock. Minute needles of rutile are very abundant. Another very common mineral is micaceous ilmenite in flakes about ·002 inch in diameter. This is either opaque or transparent, with a deep brown colour, and sometimes encloses characteristic skeletons of rutile ('sagenite'). Other constituents of some of these slates are secondary quartz, calcite, chlorite, ottrelite, garnet, *etc.*

The Cambrian *phyllites* of the Ardenne were carefully examined by Prof. Renard[3], who found that the rocks have been completely reconstituted in place. The chief mineral is usually a colourless sericitic mica, its flakes having a general parallelism with the cleavage or schistosity of the rock. This and quartz usually constitute the principal part of the bulk, and a green chlorite is also abundant. Needles of rutile and often of tourmaline lie in general parallel to the cleavage. The violet phyllites have micaceous hæmatite ('oligiste'); in others micaceous ilmenite occurs, with interpositions of rutile. Other minerals found in particular rocks are magnetite and pyrites, a manganese-garnet (spessartine) in minute crystals, ottrelite, zircon, carbonaceous matter, *etc.* The magnetite in the 'phyllade aimantifère' of Monthermé

[1] *Pr. Liverp. G. S.* (1900) viii, 464–471, pl. I, and (1901) ix, 113, 114, pl. VI, figs. E, F. See also *20th Cent. Atlas*, 52, with plate.

[2] *G. M.* 1889, 214–220; 1890, 317–320.

[3] *G. M.* 1883, 322–324 (Abstract).

was formed before the cleavage of the rock, and is surrounded by the curious eyes of chlorite and quartz already referred to. The ottrelite was formed subsequently to the cleavage of the rocks which contain it, and its flakes do not lie parallel to the cleavage-planes.

American phyllites exhibiting all the salient characteristics have been described from the Piedmont Plateau in Maryland[1], from the Lisbon group in New Hampshire[2], and from Coanicut Island, R.I.[3] A fuller account, with coloured plates, has been given by Nelson Dale[4] of the phyllites of the slate-belt of New York and Vermont. These rocks consist of sericitic mica (about 40 *per cent.*), quartz, and chlorite, with carbonates, pyrites, sometimes hæmatite, zircon, and tourmaline, and in all cases minute needles of rutile. The same author[5] has recently brought together a summary account of all the more important occurrences of workable slates in the United States.

Of ordinary slaty cleavage good illustrations are afforded by the Cambrian and Ordovician in North Wales, the Devonian in Cornwall, and some other British Palæozoic rocks. Some of these (Llanberis Slates) exhibit the deformation of originally spherical spots. Various kinds of 'eyes' about enclosed pyrites crystals may be seen at Penrhyn (fig. 66, *A*), Snowdon, Blaenau Ffestiniog, Whitesand Bay, *etc.*, and in the Cowal district of Argyllshire[6]. Special structures of the nature of *false cleavage* may be examined in the Skiddaw Slates of the Eden valley[7] (fig. 66, *B*) and of Snaefell in the Isle of Man, in the debatable rocks of the Start in South Devon[8], and in the remarkable 'gnarled' beds of Amlwch in Anglesey and of Aberdaron, *etc.*, in the west of Caernarvonshire. These last show very beautifully all the characteristic

[1] G. H. Williams, *Bull. G. S. Amer.* (1891) ii, 305–307; Diller, 317–320.

[2] Diller, 321–323.

[3] Pirsson, *A. J. S.* (1893) xlvi, 376, 377.

[4] *19th Ann. Rep. U. S. Geol. Sur.* part III (1899) 226–260, 265, 288–290, pl. xxxv–xxxix.

[5] *Bull.* 275 *U. S. Geol. Sur.* (1906).

[6] Clough, *Mem. Geol. Sur. Scot., Geol. of Cowal* (1897) 57, 80.

[7] *Q. J. G. S.* (1891) xlvii, 513, 514.

[8] *G. M.* 1889, 214–220; 1890, 317–320.

structures of 'mountain-building,' on a small scale, and such rocks afford from this point of view an interesting study. Prof. Heim, in a figure[1] illustrating the passage of an overfold into an overfault by the obliteration of the 'middle limb,' gives for the scale '$\frac{200}{1}$ to $\frac{1}{10000}$ of natural size.' Perhaps the best British districts for studying the various forms of false cleavage are the Isle of Man, where the Skiddaw Slates exhibit a great variety of interesting structures, and the Cowal district of Argyllshire[2].

[1] *Mechanismus der Gebirgsbildung* (1883) pl. xv, fig. 14.
[2] Clough, *l.c.*, 7–20.

CHAPTER XVIII.

CALCAREOUS ROCKS.

THE different kinds of limestones (Fr. calcaire, Ger. Kalkstein), consisting of carbonate of lime with various impurities or foreign materials, are almost all in great measure of organic origin. The hard parts of calcareous organisms are composed of calcite or aragonite[1], or both, with a small quantity of phosphate, *etc.* It will be seen that aragonite is always the unstable form of carbonate of lime, and tends to be converted into the stable form, calcite. It is not always easy to distinguish the two minerals in thin slices, but Meigen's method[2] may be employed with advantage.

The impure calcareous rocks may include a considerable amount of non-calcareous material; either sand-grains (calcareous grit) or finer detritus (argillaceous limestone, marl) or volcanic *débris* (calcareous tuff).

With the limestones must be classed those rocks in which dolomite takes the place of calcite. These are called dolomite-rocks or dolomites, the name dolomitic limestone or magnesian limestone being more correctly applied to rocks in which both minerals are well represented. Many dolomitic rocks can be

[1] According to Miss Kelly the substance which has been regarded as aragonite is in reality a third form of lime carbonate, which she names 'conchite'; *M. M.* (1900) xii, 363–370.

[2] It consists in boiling for a few minutes in a dilute solution of pure cobalt nitrate (freed from iron). Aragonite is stained lilac-red and calcite remains unaltered. See *M. M.* (1903) xiii, 206 and xxviii; Skeats, *Bull. Mus. Comp. Zool. Harvard* (1903) xlii, 66, 67.

proved to have originated from ordinary limestones, the magnesia which replaced part of the lime having been derived from some external source. We shall also briefly notice certain other rocks, such as some bedded iron-stones, which are genetically connected with the limestones, and some siliceous rocks of like origin.

Much valuable information concerning limestones is contained in Dr Sorby's Presidential Address to the Geological Society[1], while British limestones from various horizons have been studied by several other observers[2].

Organic fragments. Most of the fragments of calcareous organisms that form part of rocks have something in their mineral nature, their structure, or their mode of preservation, that enables us to refer them to their proper order or class, or at least sub-kingdom.

Of the *calcareous algæ* some genera are of aragonite (Halimeda), others of calcite (Lithothamnion, *etc.*). They figure largely in the deposits now forming round coral-islands[3] (fig. 67), and to a less extent in some deep-sea deposits, while the equivalents of these rocks are recognized among the Tertiary and Recent strata in various parts of the world[4]; *e.g.* the Lithothamnion Limestone and Leitha Limestone[5] of the Vienna basin. Calcareous algæ are concerned in the formation of some modern oolitic accumulations, and Girvanella, which figures largely in association with oolitic structure in rocks of various ages, is perhaps a vegetable organism; while the

[1] *Q. J. G. S.* (1879) xxxv, *Proc.* 56–95. On calcite and aragonite organisms, see also Cornish and Kendall, *G. M.* 1888, 66–73; Kendall, *Rep. Brit. Ass.* for 1896, 789–791.

[2] See especially several papers by Wethered, *Q. J. G. S.* (1888–1893) xliv–xlix, *etc.*; Jukes-Browne and Hill on Chalk, *etc.*, *ibid.* (1887–1889) xliii–xlv.

[3] See Murray and Renard, '*Challenger*' *Report*, *Deep-Sea Deposits* (1891) pl. XIII, XIV.

[4] Murray, *Scott. Geog. Mag.* (1890) vi, pl. I (Malta); Hill, *Q. J. G. S.* (1891) xlvii, 243–248, pl. IX (Barbados); Lister (and Murray), *ibid.* 602, 603 (Tonga Is.); Gregory, *Q. J. G. S.* (1892) xlviii, 538–540 (Trinidad); Hinde, *Q. J. G. S.* (1893) xlix, 230, 231 (New Hebrides). For good figures showing the structures of Lithothamnion and other calcareous algæ see Rothpletz in *Zeits. deuts. geol. Ges.* (1891) xliii, pl. XV–XVII.

[5] *20th Cent. Atlas*, 48, with plate.

peculiar algous flora of hot springs is instrumental at the present day in producing certain deposits of travertine (Mammoth Hot Springs[1]). The part played by algæ in the formation of some of the older limestones, such as the Alpine Trias, seems to be of considerable importance[2]. In some fresh-water limestones, such as those of Bembridge and of Purbeck[3], *Chara* is sometimes an important element.

The tests of calcareous *foraminifera* commonly occur entire, and are readily recognized, though in some cases the chambers become detached (Globigerina, fig. 76). The material is calcite or aragonite in different forms (answering to the division into Vitrea and Porcellanea of some authors), and probably the latter have been largely destroyed in some older limestones.

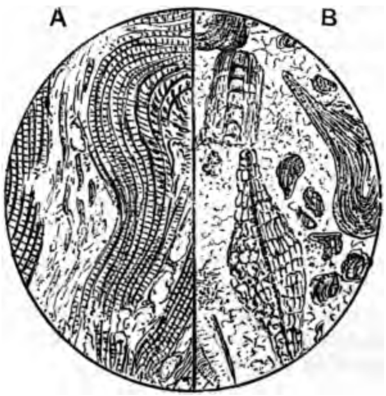

FIG. 67. RECENT ORGANIC LIMESTONES, COMPOSED LARGELY OF CALCAREOUS ALGÆ, EUA, TONGA ISLANDS; × 20.

A is a characteristic section of *Lithothamnion* [1271].
B shows foraminifera and fragments of algæ in a recrystallized calcareous matrix [1269].

[1] Weed in *9th Ann. Rep. U. S. Geol. Sur.* (1890) 642–645, *etc.*
[2] *Cf.* Seward, *Science Progress* (1894) ii, 10–26.
[3] Wethered, *Pr. Cottesw. F. N. Club* (1891) x, 101, 102, with plate.

Foraminifera occur in many shallow-water limestones[1], and make up a large part of the so-called coral-limestones[2], besides forming the bulk of extensive deep-sea deposits.

The interior of a foraminiferal test may be filled in by crystalline calcite, often with such a radial arrangement of fibres as to give a very perfect black cross in each chamber when examined between crossed nicols. In many modern sediments[3] formed near a continental shore-line the chambers are occupied by a deposit of green *glauconite*, which, by the removal of the calcareous test, may be left in the form of casts; and this seems to be the usual mode of origin of glauconite-sands, such as are found at various geological horizons[4].

The true *corals* consist, according to Dr Sorby, of little fibres, or in some cases granules, of aragonite; but it appears that calcite enters into the composition of some forms. Mr Kendall states that, while almost all the reef-building forms have aragonite skeletons, all the deep-sea corals examined by him are of calcite. Of the Rugosa some consist largely of calcite fibres roughly parallel to the outlines of the several parts of the skeleton, while the mode of preservation of others seems to indicate that they were composed largely of aragonite.

The hard parts of *echinoderms* have an unmistakable appearance. Each element (plate or joint) behaves optically as a single crystal of calcite, the larger ones showing the characteristic cleavage. The organic nature is indicated only by the external form, internal canals, *etc.* Spines of echinoids, joints of the stems of crinoids, *etc.*, may be distinguished by their size and outline (fig. 68).

[1] See, *e.g.*, Guppy, *Tr. Roy. Soc. Edin.* (1885) xxxii, pl. CXLV, figs. 1, 4 (Solomon Is.); Jennings, *G. M.* 1888, pl. XIV (Orbitoidal Limestone of Borneo).

[2] See Guppy, *The Solomon Islands, Geology, etc.* (1887) 73–76; and *Tr. Roy. Soc. Edin.* (1885) xxxii, 545–581; Lister (and Murray), *Q. J. G. S.* (1891) xlvii, 602–604 (Tonga Is.).

[3] Murray and Renard, *Deep-Sea Deposits* (1891), pl. XXIV, XXV.

[4] See, *e.g.*, Murray, *Scott. Geog. Mag.* (1890) vi, 464, 465, pl. II, fig. 2 (Malta); Gregory, *Q. J. G. S.* (1892) xlviii, 540 (Trinidad). *Cf.* Sollas, *Q. J. G. S.* (1872) xxviii, 399 (Cambridge Greensand), and Hume, *ibid.* (1897) liii, 569–571 (U. G. S. of Woodburn, Antrim).

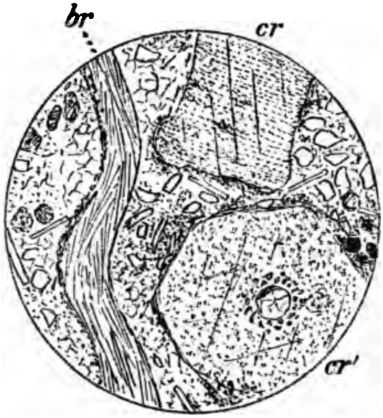

FIG. 68. LIASSIC LIMESTONE, SKYE; × 15:

showing joints of crinoid stems (*Pentacrinus*) cut longitudinally (*cr*), and transversely (*cr'*), each consisting of a single crystal of calcite; also part of a brachiopod shell (*Rhynchonella*, *br*), with its characteristic lamellar structure. The matrix is a recrystallized calcite mosaic enclosing numerous detrital grains of quartz and flakes of muscovite [1791].

The structure of the hard parts of *crustacea* is also fairly constant and quite different from the preceding. The shell is built of fibres of calcite set everywhere perpendicular to the surface, the optic axis of each fibre coinciding with its length. The general outline suffices to distinguish, *e.g.*, between entomostracan tests (abundant in many limestones) and fragments of trilobites (fig. 70, *A*).

Both calcite and aragonite enter into the composition of the *polyzoa*, and in some genera, according to Messrs Cornish and Kendall, the two occur in separate layers, the aragonite layer being in this case the outer one.

The shells of *brachiopods* are wholly of calcite, with a characteristic structure. "They are made up of laminæ, consisting of flattened fibres or prisms, often passing along more or less parallel to one another over a considerable area, but mixed up

with other systems which cross them at various angles." These laminæ lie oblique to the surface of the shell, and the individual fibres do not give strictly straight extinction (fig. 68).

The shells of *lamellibranchs* have more than one type of structure. In some ostreid genera (Ostrea, Pecten, Gryphæa, Inoceramus) the whole is of calcite in irregular flattened fibrous plates, producing a structure not unlike that of brachiopods. The shells, however, are usually of stouter build, and they tend to break up into their component prisms or fibres, which are often found detached, *e.g.*, Inoceramus in the Chalk. On the other hand, most lamellibranch shells consist originally of aragonite, and are commonly preserved only as casts in calcite mosaic (fig. 71). In some genera (Pinna, Mytilus, Spondylus) there is, according to Dr Sorby, an inner layer of aragonite protected by an outer layer of calcite, and Meigen has noted the same feature in Trigonia.

Most *gasteropods* have shells wholly of aragonite, which is readily replaced by a mosaic of crystalline calcite. In a few cases, however, *e.g.* Scalaria, the whole is of calcite (Cornish and Kendall). Others have a layer of aragonite covered by a layer of calcite: either the former (Murex) or the latter (Purpura) may form the bulk of the shell.

Of the *cephalopoda*, the shells of Nautilus and the ammonites were originally of aragonite, but the aptychi of the ammonites were of calcite. The belemnites had the guard of calcite, with a characteristic radial arrangement of fibres about an axis, but the phragmocone was of aragonite.

The tests of *pteropoda* consist, according to Mr Kendall, of aragonite, and may sometimes be recognized by their form in sections. Exceptionally they form the main constituent of a limestone, and 'pteropod ooze' is one of the deep-sea deposits now forming in some parts of the ocean.

Oolitic structure[1]. Many shallow-water limestones, of all geological ages, contain little spheroidal grains built up of

[1] On the oolitic structure and its significance see Sorby's *Presid. Address*, *l.c.*; also Teall in *Mem. Geol. Sur.*, *Jurassic Rocks of Britain*, vol. iv, pp. 8–12, pl. I, II, 1894; Wethered (papers cited). Various types of oolitic grains are described and figured by Harris, *Pr. Geol. Ass.* (1895) xiv, 59–79, pl. III, IV.

successive coats of calcareous material, and these may be so numerous as to make up the chief bulk of the rock. Such rocks are called oolitic limestones, oolites, or roestone (Ger. Rogenstein). For the coarser types, in which the grains may reach the size of peas, and are often of rather irregular or flattened form, the name pisolite (Ger. Erbsenstein) is used.

In addition to the concentric-shell arrangement, there is often a more or less evident radial structure in each grain, and closer examination shows that the minute elements which build up the successive layers are set in some cases radially, in other cases parallel to the layers.

As a result of either of these arrangements an oolitic grain, examined in section between crossed nicols, should give a black cross comparable with that observed in the spherulites of igneous rocks. Owing to the departure from true sphericity, the admixture of granular material not sharing the definite orientation described, and the effect of iron-staining and other secondary changes, an accurate black cross is not seen in every case.

The concentric layers have been formed upon a nucleus, which may be a chip of shell or other organic body, a quartz-granule, or merely a pellet of fine calcareous mud. Similar coatings are often to be seen upon fragments of shell, *etc.*, too large to be built up into round grains. Sometimes an oolitic grain has been broken and the separated fragments subsequently coated with fresh layers of calcareous deposit; or again two or three contiguous grains may be enveloped in one mantle and become a compound grain.

Oolitic grains differ as regards their material (calcite or aragonite), the orientation of their minute elements (radial or tangential), the presence or absence of finely granular calcareous matter without special orientation, or of impurities, and in other respects. One common type[1], exemplified in many British limestones, has well-marked concentric shells, each of which consists largely of minute calcite prisms or fibres set radially. There may or may not be an evident radial structure in the grain as seen in a thin slice. The black cross seen in polarized light is often imperfect or vaguely defined.

[1] Cohen (3), pl. LXIII, figs. 2, 3.

Another type is illustrated by the so-called Sprudelstein of the Carlsbad hot springs[1]. Here there are well-marked concentric shells but no radial structure. The material is aragonite, and the minute elements are set mainly tangentially to the concentric layers. This gives a well-defined black cross. Dr Sorby found recent oolites from Bahama[2] and Bermuda to have a similar constitution, but with some unoriented granular material, and he observed the same in the Bembridge Limestone of the Isle of Wight.

It is impossible to say with certainty to what extent aragonite oolitic grains have once been represented in our older rocks. In numerous instances the present structure of the grains shows that they have been recrystallized. They often consist of crystalline calcite, either in a mosaic or in wedges with a rough radial arrangement. In some cases there is an eccentric radial structure, as if the recrystallization had started at one or more points on the circumference of the grains.

It is a somewhat difficult question, how far the original structure of the different types of oolitic grains is due on the one hand to mechanical aggregation or on the other to crystallization, and it further appears that organic agency may often have played an important part. The Carlsbad Sprudelstein, the calcareous sand of Salt Lake, and other modern oolites seem to be connected with lime-secreting algæ, while Mr Wethered[3] finds the problematical organism Girvanella in many oolitic rocks of various ages. It is well seen encrusting the successive layers of large pisolitic grains in such a rock as the Pea Grit of Cheltenham, and again in some oolites, *e.g.* Wenlock Limestone (fig. 69).

Matrix of limestones. Recognizable fragments of organisms, together with oolitic grains, if present, may make up a variable part or even the chief bulk of a limestone. The remainder, in rocks which have suffered no important secondary

[1] Harris, *l.c.* pl. III, fig. 9.

[2] *Ibid.* figs. 6–8 and pp. 67–70.

[3] See papers cited below, but especially *Q. J. G. S.* (1895) li, 196–206, pl. VII, where the organic theory is extended to oolitic limestones in general: also *Proc. Cotteswold Nat. Field Club*, 1895–6.

FIG. 69. OOLITIC GRAIN IN THE WENLOCK LIMESTONE, LONGHOPE; ×6.

The concentric coats are built up largely of the interlacing tubes of *Girvanella*. [This figure was kindly furnished by Mr Wethered.]

changes, consists of a calcareous mud in which the fragments (and oolitic grains) are embedded. This finely divided material is mostly carbonate of lime, and must be in great measure derived from the attrition and disintegration of calcareous organisms, though chemical deposition may perhaps play some part, and material may be furnished by the degradation of older limestones. Iron-compounds often occur as an impurity, producing a yellow or brown stain by oxidation. Fine sand of detrital origin is often present in shallow-water limestones, and may be abundant (calcareous grits). Similarly, an admixture of argillaceous matter gives rise to argillaceous limestones and calcareous marls, or by the presence of volcanic detritus and ashes the rock becomes a calcareous tuff. In some argillaceous limestones, such as those of the English Lias, it is probable that much even of the calcareous matter is of detrital origin[1].

[1] Woodward, *Jurassic Rocks Engl. and Wales*, vol. iii (1893) 27–32; *cf.* Sollas, *Q. J. G. S.* (1879) xxxv, 492 (limestones in O. R. S. of Cardiff district) and *G. M.* 1900, 248–250.

In many limestones, and especially those belonging to the older formations, the original finely divided calcareous matter has been partially or wholly *recrystallized* into a granular calcite-mosaic of fine or sometimes comparatively coarse texture. Crystalline limestones or marbles are thus formed without any special conditions of the kind usually implied in the term metamorphism. The recrystallization seems to originate at certain points in the mass and spread. The process has a purifying effect, and ferruginous impurities often appear as if pushed before it to collect in particular patches. The recrystallized carbonate of lime is always calcite, aragonite being converted in the process to the stabler form. In such a crystalline matrix casts after aragonite shells may usually be recognized by a rather coarser mosaic and by a thin film of impurities marking the original outline, even when they are not coated in oolitic fashion (fig. 71).

The recrystallized calcite usually forms a more or less finely granular mosaic in the interstices between the organic fragments, oolitic grains, *etc.* In some cases, however, the individual crystal-grains of calcite are of large size, so as to enclose numerous oolitic granules, shell-fragments, *etc.*, thus giving a structure like the ophitic and pœcilitic in some igneous rocks. This has been remarked by Dr Teall in some of the oolitic building-stones of the Lincolnshire Limestone (Barnack, Ketton, Ancaster). In certain coarse-textured marbles the new-formed calcite occurs partly as a crystal outgrowth of fragments of crinoids, *etc.*, comparable with the quartz-cement of many quartzites (Clifton, Keisley, *etc.*).

The quartz-sand, *etc.*, occurring as impurities in many limestones can be easily isolated by dissolving the rock in dilute acid, and sometimes present points of interest[1]. Minute perfect crystals of quartz may occur, sometimes evidently formed by secondary outgrowth from detrital quartz-grains (Clifton).

Some British limestones[2]. After what has been said

[1] Wethered (Carboniferous), *Q. J. G. S.* (1888) xliv, 186-198; (Inferior Oolite) *ibid.* (1891) xlvii, 559–569.

[2] Of American limestones a number of typical examples are described by Diller, *Educ. Ser. Rocks*, 102–132.

in the foregoing paragraphs, a few remarks on some of the more important calcareous formations of this country will be sufficient to illustrate our subject.

The Cambrian limestones of Durness, Assynt, and Skye are remarkably free from detrital impurities. They are in great part dolomitized, presenting a saccharoid texture.

The Bala Limestone of North Wales is sometimes a fine calcareous mud-stone, sometimes recrystallized. The most conspicuous organic fragments are those of crinoids, which are in places very abundant, and polyzoa are also found. The Hirnant Limestone[1] has a peculiar type of oolitic structure, the grains having a chalcedonic skeleton and concentric zones rendered opaque by finely divided carbon. The Coniston Limestone of Westmorland is in its purer parts usually recrystallized throughout to a granular mass, in which the original characters are lost. In places it is dolomitized[2] (fig. 72). In its lower part it contains much non-calcareous material, chiefly volcanic.

The Wenlock Limestone of Dudley[3], with a recrystallized matrix, still preserves abundant organic fragments, especially those of crinoids, entomostracans, trilobites, corals, polyzoans, and brachiopods. It sometimes has as much as 30 *per cent.* of foreign detrital material. At Malvern the rock is largely oolitic[4], the grains being set in a recrystallized matrix, and sometimes themselves recrystallized (the Wych). Composite and broken oolitic grains also occur (Croft). The Aymestry Limestone, from Dr Sorby's description[5], is very like the Wenlock.

Dr Sorby[6] has pointed out many interesting features in the Devonian limestones of Devonshire. The recognizable organic

[1] Fulcher, *G. M.* 1892, 114–117, pl. IV; Harris, *Pr. Geol. Ass.* (1895) xiv, 78, pl. IV, fig. 10.

[2] *Q. J. G. S.* (1893) xlix, 367.

[3] *20th Cent. Atlas*, 40, with plate.

[4] Adye's *Stud. Micropetr.* 19, 20, pl. IV, fig. 2.

[5] *L.c.* p. 60.

[6] *Phil. Mag.* (1856) ser. 4, xi, 20–37. See also Wethered, *Q. J. G. S.* (1892) xlviii, 377–387, pl. IX.

fragments are chiefly of crinoids and corals, and the finely divided calcareous matter is probably derived from the degradation of coral skeletons. This fine material has often been recrystallized in the usual fashion, the impurities being segregated into patches of finer texture. Again, rhombohedral crystals of dolomite (often ferriferous) have frequently been formed in the rocks[1], and some have become true dolomite-rocks, while a little pyrites, partly oxidized, is not uncommon. Many of the rocks show slaty cleavage in every respect similar to that noticed in argillaceous strata.

The Carboniferous limestones of Clifton, Bristol[2], are largely built of recognizable organic fragments. Crinoids and sometimes ostracods are especially abundant in the Lower Limestones, foraminifera and the problematical organism Calcisphera in the Middle[3]. Numerous oolitic beds occur, and in some of these Mr Wethered[4] has found the oolitic structure to be connected with the growth of Girvanella. In others the oolitic grains are in some measure replaced by iron-oxides and silica, and some of the organic fragments (especially of polyzoa) also show a ferruginous replacement (fig. 70, *B*). The interstitial calcareous mud is usually recrystallized as a rather coarse calcite-mosaic, and dolomitization occurs at some horizons, as is also frequently the case in the Carboniferous Limestone in other parts of Britain. In the North of England the most frequent of the recognizable organic fragments are in many cases those of crinoids, and at some horizons in Derbyshire and Yorkshire these constitute the main bulk of the rock, but fragments of brachiopods, corals, polyzoa, and algæ also occur,

[1] Wethered, *l.c.* fig. on p. 381. On the partial silicification of some beds see Chapman, *G. M.* 1893, 100–104.

[2] *20th Cent. Atlas*, 17, 18, with plate.

[3] Wethered, *G. M.* 1899, 78, 79, and *Rep. Brit. Ass.* for 1898, 862, 863; see also *G. M.* 1886, 529–540, pl. XIV, XVI (Forest of Dean), and Morton's *Geol. of Liverpool* (2nd ed., 1891) 25–27 (Flintshire). The microscopic characters of some Carboniferous limestones from North Wales and from Somerset are described by Beasley, *Pr. Liverp. G. S.* (1879) iii, 359–361.

[4] *Q. J. G. S.* (1890) xlvi, 270–274, pl. XI: *cf.* Harris, *Pr. Geol. Ass.* (1895) xiv, 76, 77, pl. IV, figs. 7, 8.

and may be abundant, while foraminifera are often very plentiful[1].

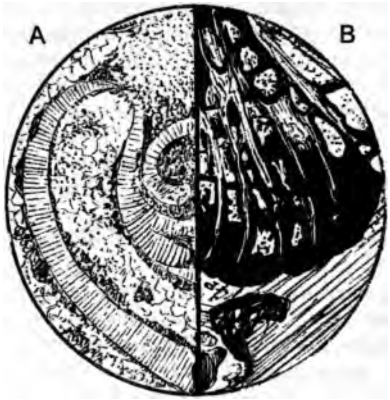

FIG. 70. CARBONIFEROUS LIMESTONE, CLIFTON, BRISTOL; × 20.

A shows a portion of a trilobite with the characteristic structure of the crustacea [981].

B, polyzoa replaced by opaque limonite, mixed with silica, in a matrix of coarsely crystalline calcite [972].

The Permian Magnesian Limestone is in general a true dolomite-rock, and in most cases all minute original structures have been lost in the changes which converted the rock to a granular mass of dolomite. When organic fragments are recognizable they are most frequently those of shells and polyzoa. Locally in South Yorkshire the latter bodies make up almost the whole of the rock (Brodsworth, Cadeby, *etc.*). Near Abergele in North Wales foraminifera and corals form a large part. The Magnesian Limestone is, as a rule, tolerably free from foreign detrital matter, but locally it becomes arenaceous. Dolomitic sandstones occur near Mansfield, and the attenuated representative of the Magnesian Limestone in Westmorland is full of angular quartz-grains.

[1] The Saccamina Limestone of Northumberland is an example of a Carboniferous rock composed essentially of foraminifera. See also *20th Cent. Atlas*, 71, 72, with plate (Endothyra Limestone, near Leek, Staff.).

In the Lower Oolites of the Cotteswold and Bath districts[1] fragments of shells, crinoids, and polyzoa, tests of foraminifera and other organic remains are recognized in variable proportions. Most of these limestones are oolitic, but the original structure of the oolitic grains is often destroyed by recrystallization. In the best-preserved examples Girvanella is detected at various horizons, and it is specially well exhibited in the coarse pisolite known as the 'Pea Grit[2].' The rocks contain various small proportions of insoluble residue, consisting of detrital mineral fragments (quartz, *etc.*). The Lincolnshire Limestone and Millepore Oolite of the North of England[3] are made up largely of oolitic grains of the ordinary type, consisting of a nucleus of a shell-fragment, a quartz-grain, or a brown pellet of mud, surrounded by numerous iron-stained coats, in which a radial structure is sometimes discernible (fig. 71). The organic fragments include chips of brachiopods and Pecten, recrystallized fragments of aragonite shells, foraminifera, valves of ostracods, pieces of echinoderms, *etc.*, in different beds : *e.g.* abundant brachiopod spines in the Rhynchonella spinosa beds. The general matrix of fine calcareous mud is almost always converted into a crystalline calcite-mosaic with localisation of the ferruginous impurities, and most of the rocks contain a considerable amount of angular quartz-sand. This last feature is more prominent in the Scarborough Limestone and the Cornbrash. The former, especially in certain nodular bands, is often an iron-stone consisting of minute rhombohedra of chalybite, with no calcite remaining except in the fragments of shells.

The Coral Oolite of Malton is another good specimen of an oolitic limestone with recrystallized matrix. Besides foraminifera, crinoid fragments, *etc.*, it contains abundant remains of aragonite gasteropods replaced by calcite mosaic. The oolitic grains are sometimes large enough to be termed pisolitic, but

[1] Wethered, *Q. J. G. S.* (1890) xlvi, 274–277, pl. xi ; (1891) xlvii, 550–569, pl. xx ; *Pr. Cottesw. F. N. Club* (1892) x, 119, 120 ; Harris, *Pr. Geol. Ass.* (1895) xiv, 70–72, 75, 76 ; pl. iv, figs. 1, 2, 6.

[2] See also Wethered, *G. M.* 1889, 197, 198, pl. vi.

[3] *Naturalist*, 1890, 300–304. For figures of various Lower Oolitic limestones see *Mem. Geol. Sur., Jurassic Rocks*, vol. iv, pl. i.

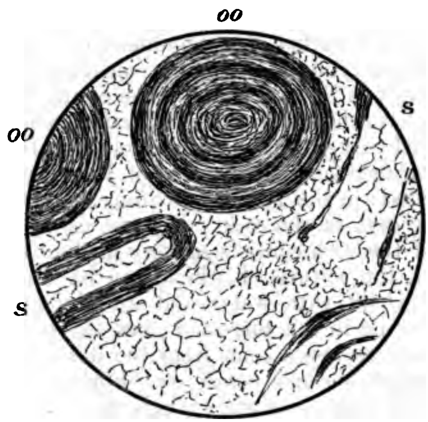

FIG. 71. OOLITIC LIMESTONE, MILLEPORE OOLITE, WHARRAM, EAST YORKSHIRE; ×20:

showing oolitic grains (*oo*) and chips of lamellibranch shells (*s*) in a matrix which has recrystallized as a mosaic of clear calcite [1794].

the Girvanella noticed by Mr Wethered[1] in the Osmington pisolite, near Weymouth, is not yet recorded from Yorkshire. The last named author (*l.c.*) has described the Portland rocks[2] with their recrystallized oolitic grains. The silicification of some beds in that district will be referred to below.

The microscopic characters of the English Chalk have been described by Dr Sorby[3], Messrs W. Hill and Jukes-Browne[4],

[1] *G. M.* 1889, 197, pl. VI, fig. 9; *Q. J. G. S.* (1890) xlvi, 277–279, pl. XI, figs. 6–8.

[2] On the Portland Oolite see also Harris, *Pr. Geol. Ass.* (1895) xiv, 72–74, pl. IV, figs. 3, 4; Teall, *Mem. Geol. Sur., Jurassic Rocks*, vol. V (1895) 186.

[3] *Q. J. G. S.* (1879) xxxv, Proc. 48, 49.

[4] *Q. J. G. S.* (1886-9) xlii, 228–230 (Cambridgeshire and Hertfordshire); 242, 243, Dover; xliii, 580–585 (W. Suffolk and Norfolk); xliv, 355–357 (Lincolnshire and Yorkshire); xlv, 406–413 (Berkshire and Wiltshire); *Naturalist*, 1906, 213, 214, pl. XVIII (Upp. Chalk, Lincolnshire). See also Hume, *Chem. and Micro-miner. Researches on the Up. Cret. Zones of the S. of Eng.* (1893) and on the Chalk of Antrim, *Q. J. G. S.* (1897) liii, 568–584. For a general summary of the microscopic characters of the English Chalk see Jukes-Browne, *Pr. Yorks. Geol. Pol. Soc.* (1895) xii,

and others. The tests of foraminifera, and especially detached chambers of Globigerina, are abundant in many examples, though they rarely form the chief constituent of the rock. These are empty in the soft chalk of the South, but filled with calcite in the hard chalk of Yorkshire. Radiolarian remains have been preserved only exceptionally[1]. Molluscan fragments, and especially the detached shell-prisms of Inoceramus, are often well represented: in the Totternhoe Stone shell-fragments form 60 to 70 *per cent.* of the rock. In most cases, however, the great bulk of the rock consists of very finely divided calcareous material, the nature of which can be studied only by rubbing the chalk with water and examining the powder. Coccoliths abound in this fine mud[2], but the minute granules are mostly such as would come from the destruction and dissolution of aragonite shells, corals, *etc.* Foreign detrital matter is rare in the Chalk, except at certain horizons, but is abundant in the Red Chalk of Hunstanton, Lincolnshire, and Yorkshire[3]. The Cambridge Greensand has rather large quartz-grains, with some mica. It also contains a considerable number of glauconite grains, usually as perfect internal casts of foraminifera[4], and glauconite occurs at some higher horizons in smaller quantity. Sponge-spicules may be found in some examples. Those in the Lower Chalk of Berkshire and Wiltshire are sometimes preserved in the original colloid silica, sometimes replaced by calcite, while little globules of colloid silica (·0006 inch in diameter) occur in the rock. Glauconite grains are abundant in some parts of the 'Chalk Rock,' as well as in the Chalk Marl[5].

Deep-sea deposits. Beyond the broad belt of deposits now forming along the continental coast-lines and deriving

385–395; and for more detailed information Hill, *Mem. Geol. Sur., Cret. Rocks*, vol. ii, chaps. XXII, XXIII, XLIII (1903) and vol. iii, chap. XXII (1904).

[1] Hill and Jukes-Browne, *Q. J. G. S.* (1895) li, 600-603 (Melbourn rock).

[2] On coccoliths in the Chalk see Sorby, *Ann. Mag. Nat. Hist.* (1861) ser. 3, viii, 193–200.

[3] On the mineral constitution of the Red Chalk and its insoluble residue see *Mem. Geol. Sur., Cret. Rocks*, vol. i (1900) 345, 346.

[4] Sollas, *Q. J. G. S.* (1872) xxviii, 399.

[5] Hume, *l.c.* 55, 56.

their material in some degree from the waste of the land and from shallow-water organisms, and apart too from the special accumulations forming round coral- and volcanic islands, extensive calcareous deposits are found covering large areas of the floor of the deep ocean down to about 2800 fathoms. The most widely spread of these deposits is *globigerina-ooze*, consisting largely of the tests of Globigerina and other foraminifera[1], together with a smaller proportion of other organisms, such as siliceous radiolaria, and some non-calcareous matter of volcanic origin. Associated with the foraminiferal remains are immense numbers of very minute elliptic disc-shaped bodies, to which Prof. Huxley gave the name *coccoliths*[2]. These calcareous discs have been detached from the surface of certain globular organisms named coccospheres, referred to the algæ. The coccoliths have a diameter of ·0002 to ·0005 inch. Associated with them are often other minute bodies in the form of slender rods with a crutch-like termination (rhabdoliths). Coccoliths and rhabdoliths are very characteristic of the deep-sea calcareous deposits, though not confined to them.

The inorganic residue of these rocks is essentially of volcanic material in a state of extremely fine division, and corresponds with the 'red clay' already noticed (p. 247).

Various foraminiferal and other limestones have been described among Tertiary and Recent strata which approximate, in some cases very closely, to the essential characters of true deep-sea deposits[3].

For the sake of completeness the deep-sea deposits of siliceous composition may also be mentioned. The 'Challenger' Expedition[4] has shown that these occur over extensive tracts of the ocean-floor in its deepest portions. Characteristic types are the *diatom-ooze*, essentially an accumulation of

[1] Murray and Renard, *Deep-Sea Deposits* (1891), pl. XI, figs. 1, 5, 6; XII; XV, fig. 2; *20th Cent. Atlas*, 4–6, with plate.

[2] Murray and Renard, *l.c.* pl. XI, figs. 3, 4. See also Wallich, *Ann. Mag. Nat. Hist.* (1861) ser. 3, viii, 52–56.

[3] *E.g.* Hill, *Q. J. G. S.* (1892) xlviii, 179 (Barbados).

[4] See especially Murray and Renard, *Challenger Rep.*, *Deep-Sea Deposits* (1891) with plates (pl. XV, *etc.*).

the frustules of diatoms, and the *radiolarian ooze*, made up mainly of the tests of radiolaria. There may be some admixture of finely divided volcanic material or its decomposition-products or of foraminiferal remains. The equivalents of this radiolarian ooze are found in Recent and Tertiary *radiolarian earths* such as those of Barbados[1] and Trinidad[2], and, in a compacted form, in the *radiolarian cherts* of some of the older formations. The Ordovician cherts of the south of Scotland, described by Dr Hinde[3], show in slices a faint cloudy appearance, giving a mottled effect between crossed nicols, but are frequently veined and stained with dark brown. In the transparent parts the radiolaria show as shadowy circles defined by their interior being somewhat lighter than the surrounding matrix. In the stained parts the tests are replaced by a dark substance, and may retain much of their original structure. The most considerable development of radiolarian cherts known is in the Devonian of Tamworth, N. S. W.[4] Here a deep-sea origin is inadmissible.

Metasomatic changes in limestones. In many rocks which may be assumed to have been once ordinary limestones, the carbonate of lime has been partly, or even wholly, replaced by other substances, thus producing a change in the chemical composition of the rock (metasomatism). The most common of such changes is that in which calcite is converted into dolomite by the replacement of half its lime by magnesia (*dolomitization*). It seems to be clearly established that calcite and dolomite are not chemically isomorphous substances, but each has its own definite composition. The molecular ratio CaO : MgO in dolomite is

[1] See Jukes-Browne and Harrison, *Q. J. G. S.* (1892) xlviii, 174, 175; Nicholson and Lydekker, p. 34, fig. 12.

[2] Gregory, *Q. J. G. S.* (1892) xlviii, 538, 539. On a radiolarian earth from S. Australia see Hinde, *Q. J. G. S.* (1893) xlix, 221, pl. v.

[3] *Ann. Mag. Nat. Hist.* (1890) ser. 6, vi, 41–47, pl. III, IV. On a somewhat similar rock from Mullion Island, Cornwall, see Hinde, *Q. J. G. S.* (1893) xlix, 215, pl. IV; on radiolarian cherts in the Culm of Devon, Cornwall, and Somerset, see Hinde and Fox, *Q. J. G. S.* (1895) li, 629–634.

[4] Edgworth David and Pittman, *Q. J. G. S.* (1899) lv, 33, 34; Hinde, *ibid.* 38–42, pl. VIII, IX.

always unity, and a higher ratio in the bulk-analysis of a dolomitic rock indicates a mixture of dolomite and calcite.

In the finely granular mosaic which such rocks often present it may be difficult to distinguish the two minerals from one another without chemical tests[1]. One criterion is the much stronger tendency of dolomite to develope crystal outlines, always those of the primitive rhombohedron (fig. 72). In coarse-grained rocks the more marked cleavage-traces of calcite and the frequency in it of lamellar twinning[2] help to distinguish it from dolomite. Again, calcite is colourless in slices, while dolomite often (but not always) has a yellow or yellowish-brown tint. This coloration is probably due to iron. It may be remarked that another mineral of the same group is sometimes met with, *viz.*—chalybite, or siderite, the ferrous

FIG. 72. DOLOMITIZED LIMESTONE IN UPPER CONISTON LIMESTONE, SHAP WELLS, WESTMORLAND; ×20.

The dolomite is here in good rhombohedra with a zonary structure marked by inclusions: some calcite remains as a clear mosaic [1616].

[1] Lemberg has given a microchemical test applicable to rock-slices. With a solution of aluminium chloride and logwood calcite becomes stained in five or ten minutes to a violet colour, while dolomite is unaffected.

[2] Cohen (3) pl. XXVII, fig. 4 (Carrara marble).

carbonate. This often builds little rhombs with curved outlines. It is of a somewhat deeper brown tint than dolomite, and in many cases encloses little opaque specks or minute crystals of pyrites (fig. 73, *C, D*).

In many cases the rocks give evidence of shrinkage during the process of dolomitization. There are often crevices and cavities, which, however, may be filled subsequently by an infiltration of calcite. Some dolomitized oolitic limestones show a little cavity in the centre of each oolitic grain (Magnesian Limestone near Hartlepool).

Good examples of more or less perfectly dolomitized rocks occur in the Durness Limestone of Sutherland, the Bala and Coniston Limestones, the Devonian of Devonshire[1], the Carboniferous Limestone of many parts of England and Ireland, and the Permian Magnesian Limestone.

The dolomitized Carboniferous Limestones of Derbyshire[2], the Isle of Man, South Wales[3], and Ireland[4] are in general highly crystalline, and all trace of organic structures is obliterated. A common type seems to be that in which the predominant dolomite, in more or less imperfect crystals, is cemented by calcite. This becomes evident on weathering, when the removal of the calcite sets the dolomite crystals free. The rocks are always more or less cellular or porous, but the cavities are commonly filled, or lined in drusy fashion, by calcite.

Dr Sorby describes the Magnesian Limestone north of Nottingham as comparatively coarse-textured, with evident rhombohedral crystals. The usual type in Durham is often fine-grained, the elements being of irregular form. Some times an interlocking arrangement of the granules, aided by the presence of little vacant spaces, gives a certain flexibility to the rock[5] (Marsden). The little cavities or pores are,

[1] Adye's *Stud. Micropetr.* 8–10, pl. II, fig. 1.

[2] Rutley, *Q. J. G. S.* (1894) l, 381, 382, pl. XIX, figs. 5, 6; *20th Cent. Atlas*, 63, 64, and plate.

[3] Watts, *Mem. Geol. Sur.*, *S. Wales Coalfield*, part II (1900) 34–36, pl. I.

[4] Hardman, *Pr. Roy. Ir. Acad.* (1876) ser. 2, ii, 723-726.

[5] Card, *G. M.* 1892, 117–124.

however, as in other dolomitic rocks, often occupied by crystalline calcite. The well-known nodules of Marsden and Sunderland, several inches in diameter and with well-marked radial crystallization, are of calcite with but little carbonate of magnesia[1].

Again, certain *ironstones* have evidently been formed[2] by metasomatic changes from limestones. The process consists first in the replacement of calcite by ferrous carbonate (chalybite), and further, in many cases, in an oxidation of the latter, giving rise to magnetite, hæmatite, or limonite. The oolitic limestones seem to be specially liable to this kind of alteration, and the oolitic grains themselves show the most advanced stage, the outer part of each grain being converted into magnetite or limonite, while the matrix of the rock remains as chalybite or in part calcite (fig. 73, *A* and *B*, illustrating successive stages). The chalybite matrix is fine-textured, and the mineral often shows imperfect crystal-form, each crystal sometimes enclosing a nucleus of decomposing pyrites (fig. 73, *D*). In a more advanced stage of change patches of limonite replace the chalybite of the matrix, and even calcite shells of Pecten, *etc.*, are converted into hæmatite or limonite (*e.g.* the Dogger of the Peak in Yorkshire)[3]. The oxidation does not take place in the more argillaceous ironstones, the iron remaining there in the form of carbonate. Valuable oolitic ironstones are worked in this country. That of Rosedale (Dogger) is magnetite, the Cleveland Main Seam[4] (Middle Lias) shows various stages of transformation and various admixtures of earthy matter, the Jurassic ores of Northampton and Rutland have specially the limonite type of alteration, and the Neocomian ores of Tealby and Claxby in Lincolnshire are similar. An oolitic ironstone with more gritty impurities

[1] Garwood, *G. M.* 1891, 434–440.

[2] See Sorby, *l.c.* pp. 54, 55; Judd, *Geol. of Rutland*, 117–138; Hudleston, *Pr. Geol. Ass.* (1889) xi, 117–127; Cole and Jennings, *Q. J. G. S.* (1889) xlv, 426, 427; Teall in *Mem. Geol. Sur.*, *Jurassic Rocks of Britain*, vol. iii, p. 302; vol. iv, pl. II, *etc.*

[3] Sorby, *Naturalist*, 1906, 354, 357.

[4] For figures of this and other oolitic ironstones see *Mem. Geol. Sur.*, *Jurassic Rocks*, vol. iv, pl. II.

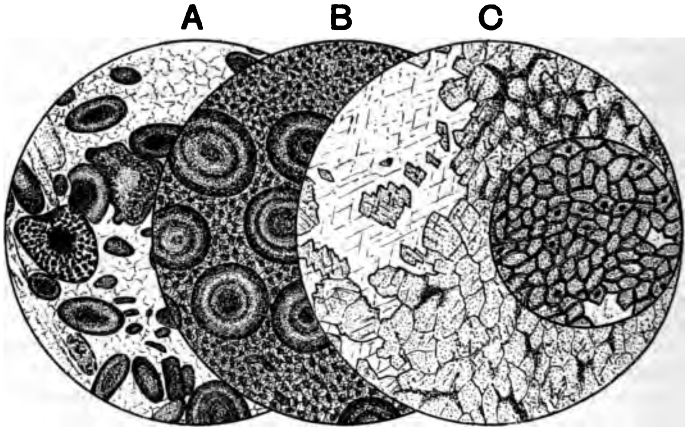

FIG. 73. IRONSTONES; × 20.

A. Oolitic Limestone in an early stage of conversion, Lias, Frodingham, Lincolnshire. The oolitic grains and certain classes of organic fragments are replaced by iron-oxide, the matrix being still a mosaic of calcite [2194].

B. Oolitic Ironstone, Neocomian, Claxby, Lincolnshire. Here the matrix has been replaced by chalybite, and this oxidized in spots [2524].

C. Ironstone, Dogger, Blea Wyke, Yorkshire; showing an aggregate of crystalline chalybite, with some residual clear calcite [1792].

D. (Small inset circle, × 100). Ironstone in Lower Oolites, Scarborough. A fine-grained aggregate of chalybite, with only incipient oxidation; some grains containing a nucleus of pyrites [2791].

occurs at Abbotsbury and Westbury in the Corallian group of the Isle of Purbeck[1].

The best known bedded ironstone of this kind in America is the Clinton ore, which occurs in the Silurian of the eastern States, and is worked at Clinton, N. Y., Birmingham, Ala., and elsewhere. Some beds are truly oolitic, while others

[1] Strahan, *Mem. Geol. Sur., Geol. I. Purb.* (1898) 39; Teall in *Mem. Geol. Sur., Jurassic Rocks*, vol. v (1895) 324; see also vol. iv, pl. II, fig. 12.

have a quasi-oolitic appearance, the grains being rolled fragments of polyzoans replaced by iron-oxide. While some difference of opinion exists as regards the origin of the ore, it seems probable that it is, at least in great part, formed from limestone[1].

If the grains of an oolitic iron-ore be dissolved by acid, each leaves a shell or skeleton of silica, soluble in caustic potash. This silica must have been introduced at some stage of the alteration of the original limestone. A similar siliceous skeleton is sometimes found in the grains of oolitic limestones where no ferruginous replacement has taken place, or, again, silica may more or less replace the calcareous matter between the grains[2]. Although *silicification* is perhaps less common than some of the other metasomatic changes noticed above, it is found in numerous limestones of various ages. Sometimes the replacement of carbonate of lime by silica is confined to the organic remains, but in other cases it affects the whole body of the rock (*e.g.* some cherts). Parts of the Carboniferous limestones of Clifton show examples of oolitic grains and organic fragments replaced by a mixture of limonite and silica. Good examples of cherts formed by the silicification of limestone (matrix and fossils alike) are found in the Portland Beds of the South of England[3].

An almost purely siliceous rock from eastern Pennsylvania[4] shows a beautiful oolitic structure, each little sphere, about ·04 inch in diameter, consisting of numerous concentric coats surrounding a nucleus, and the interspaces being also occupied by silica. Here there must evidently have been a molecular replacement of carbonate of lime by silica, and indeed associated rocks show various stages of partial replacement. Some cherts in the Durness Limestone of Sutherland tell the same story, the oolitic structure being still discernible (Stronchrubie

[1] See Foerste, *A. J. S.* (1891) xli, 28, 29; Kimball, *Amer. Geol.* (1891) viii, 356, 357; Smyth, *A. J. S.* (1892) xliii, 487–496; Diller, 138–140.

[2] Chapman, *G. M.* 1893, 100–104 (Devonian, Ilfracombe).

[3] Miss Raisin, *Pr. Geol. Ass.* (1903) xviii, 76–80, pl. XIV, XV.

[4] Barbour and Torrey, *A. J. S.* (1890) xl, 247–249, with figures. Similar rocks occur at several localities in Missouri; Hovey, *ibid.* (1894) xlviii, 404, 405; Harris, *Pr. Geol. Ass.* (1895) xiv, 78, pl. IV, fig. 9.

near Ichnadamph). Similar oolitic cherts occur in the Corallian of Yorkshire, in the Portlandian of St Alban's Head[1], and in the Carboniferous of South Wales[2].

Still another metasomatic change met with in some calcareous rocks is *phosphatization*. This usually affects some or all of the organic remains, or phosphatic nodules are formed having fossils of various kinds as nuclei. The phosphate of lime is presumably itself derived from organic bodies, but it is not clear to what extent it has been supplied contemporaneously with the deposit which contains the nodules. Deposits rich in phosphate occur at various horizons in the formations of this country: the Cambridge Greensand may be taken as an example, where the fossils are largely phosphatized and also serve to some extent as the nuclei of nodules. In other instances phosphate of lime occurs as casts of foraminifera[3] or as grains more or less definitely replacing those bodies[4]. Phosphatic deposits are now forming in the ocean, both within the littoral belt and in connection with the globigerina-ooze, *etc.*[5]

[1] Teall, *Mem. Geol. Sur., Geol. I. Purbeck* (1898) 63, and *Jurassic Rocks*, vol. v (1895) 186.

[2] Watts, *Mem. Geol. Sur., S. Wales Coalfield*, part II (1900), 36.

[3] Chapman, *Q. J. G. S.* (1892) xlviii, 514–518, pl. xv.

[4] Strahan, *Q. J. G. S.* (1891) xlvii, 357–362 (Chalk, Taplow); (1896) lii, 465 (Lewes).

[5] Murray and Renard, '*Challenger*' *Report, Deep-Sea Deposits* (1891), pl. xx.

CHAPTER XIX.

PYROCLASTIC ROCKS.

THE fragmental volcanic rocks are in general the products of explosive action[1]. The ejected material varies from the finest dust to pieces several inches, or even feet, in diameter, but the coarsest types do not require special notice here.

What is known as *volcanic dust* or fine ash is no doubt partly due to the comminution of rocks and crystals by friction during the explosion, but a great part of it must represent lava blown out from the vent in liquid form and solidified almost instantaneously in the air. It doubtless solidifies as glass, but may, of course, be subsequently devitrified. The bodies known as volcanic *bombs* and *lapilli* are of very various sizes. They may have spheroidal or more peculiar forms; or again they may be irregularly shaped or fitted together. Some kind of concentric structure, with a nucleus and an outer crust, is often seen, or the exterior may be scoriaceous. In many volcanic accumulations *crystals* play an important part. They are commonly idiomorphic, though frequently broken, and belong to the minerals common in lavas. They may sometimes be torn from solid rocks, but more generally they must have been contained in a fluid matrix before the eruption. We also find *rock-fragments*, either angular or, in submarine deposits, partly rolled and worn. They are commonly of lava for the

[1] The exceptions ('flow-breccias,' *etc.*) are not important for our present purpose.

most part, shattered and blown out by the explosion; but we also find pieces of igneous rocks which must have come from greater depths, or fragments of slate, grit, limestone, *etc.*, representing strata broken through, and often showing evident metamorphism. The larger 'ejected blocks' are frequently of these foreign and non-volcanic rocks.

The rocks formed by the accumulation of these various materials have received many names. The term *ash*, applied to the finer incoherent products of modern volcanoes, is sometimes used in a more extended sense: but the older, more or less compacted, deposits of ash-material are usually called *tuffs*. A large proportion of them were evidently laid down under water: subaërial accumulations have less frequently been preserved from destruction. Rosenbusch, in describing the ancient acid tuffs, divides them into compact tuffs, crystal-tuffs, and agglomeratic tuffs, and the division may be applied to rocks of other composition; but, since the relative proportions of dust, crystals, and lapilli, *etc.*, may vary to any extent, no precise divisional lines can be drawn. If angular rock-fragments be largely represented, the deposit is termed a *volcanic breccia*, or if the fragments be rounded, a *volcanic conglomerate*.

According to the nature of the material, the rocks may often be spoken of as 'rhyolite-tuff,' 'trachyte-tuff,' *etc.*, or, again, 'andesite-breccia,' 'trachyte-conglomerate,' and so forth; but, owing to the admixture of various materials, the rocks do not always correspond exactly even with contemporaneous lavas directly associated with them.

Further, when deposited under water, the volcanic material may become mixed with ordinary detritus or with calcareous matter, and so we have earthy tuffs, calcareous tuffs, *etc.*, some of which are fossiliferous.

General characters. Fragmental volcanic rocks have received much less minute study than lavas, and indeed present greater difficulty, requiring for the finer material the use of high magnifying powers.

Typical volcanic dust in a fresh state seems to consist essentially of glass-particles, with only a minor proportion of comminuted crystals and microlites. The glass-fragments

have a peculiar structure and a characteristic form. This is due to the immense number of contained steam-bubbles, which were drawn out into minute tubes, causing the glass to break into linear shapes with a longitudinal striation. The glass is distinguished from comminuted felspar by the absence of true rectilineal boundaries and the isotropic character. The minute fragments are colourless, except in the case of basic glasses, which may be of a brown tint. According to Murray and Renard[1], the characteristic appearance of these glass-fragments may be recognized even in excessively small particles (less than ·0002 inch), while the distinctive properties of most minerals cannot be detected in fragments of smaller dimensions than ·002 inch. The minerals commonly recognized are the familiar constituents of volcanic rocks—especially plagioclase, pyroxenes, and magnetite[2], for many of these very fine volcanic dusts are of the nature of pyroxene-andesite. The crystals are often coated with glass or have glass adherent. The authors named find precisely similar material to be widely distributed in modern deep-sea deposits, where it accumulates from the fall of wind-borne dust and the disintegration of floating pumice.

In tuffs formed not far from a volcanic centre, crystals of recognizable size, perfect or broken, are often embedded in a fine-textured matrix. These frequently show a characteristic arrangement, standing with their long axes vertical or roughly perpendicular to the lamination of the matrix, as if dropped into their place from above (fig. 75).

In any except comparatively young tuffs the original character of the finely divided material is largely obscured by secondary changes, the loose texture of the deposits rendering them peculiarly liable to alteration. According to the nature of the rock, such minerals as quartz, sericitic mica, chlorite, calcite, *etc.*, are developed at the expense of the original dust. Silicification is very common in the acid tuffs. Fragments of lava naturally suffer less than the enclosing matrix, but if glassy they readily become altered. In particular the more basic glasses, such as basalt and augite-andesite, are hydrated

[1] See especially *Nature* (1884) xxix, 585–589.

[2] Fouqué and Michel Lévy, pl. XIII, fig. 4.

and converted into the transparent brown or yellow, or more rarely green, substance known as palagonite[1].

In some cases it is very difficult to distinguish compact rhyolite-tuffs, silicified or otherwise altered, from rhyolites which have undergone similar changes, the lamination of the one and the flow-structure of the other often increasing the resemblance. When enclosed crystals occur, their characteristic orientation, as noted above, will often furnish a clue; or again the occurrence of fragments with concave outlines[2] (Ger. Bogenstructur) is sufficiently suggestive (fig. 74). This latter feature, resulting from the breaking up of pumiceous or highly vesicular lavas, is highly characteristic, especially in rhyolite-tuffs. Old tuffs of andesitic or basaltic composition, when more or less cleaved and impregnated with secondary chlorite, calcite, and other substances, may sometimes be mistaken for crushed lavas of like composition, or *vice versâ*, unless distinct fragments, such as lapilli, can be detected. These lapilli can often be recognized by a rounded outline, or a vesicular structure, or an opacity due to finely divided magnetite[3].

It will easily be understood that fine-textured tuffs may exhibit precisely the same phenomena of slaty cleavage as those seen in argillaceous sediments, while the coarser pyroclastic rocks (volcanic breccias and agglomerates) are more readily crushed than solid rocks such as lavas.

Illustrative examples. Without attempting to deal systematically with the great variety of tuffs, agglomerates, *etc.*, it will be sufficient to draw attention to a few, which have been already described, or illustrate various points of interest.

The Ordovician volcanic series in Britain affords many examples of *rhyolite-tuffs*. They are well represented in the

[1] For some discussion of the nature of this substance, see Zirkel, *Micro. Petr. Fortieth Parallel*, pp. 273-275 (1876). The basic glass which has not suffered hydration is sometimes termed sideromelane: see also Murray and Renard, *Challenger Rep.*, *Deep-Sea Deposits* (1891).

[2] For chromolithograph illustrating this structure, see Berwerth, Lief. III.

[3] *Cf.*, *e.g.*, Teall's figure of one of the Llanberis tuffs, pl. XLV, fig. 1.

Snowdon district. Embedded crystals usually occur (Glyder Fawr, *etc.*), but do not make up any large part of the mass. There are, however, beds made up very largely of small rock-fragments and broken crystals, lying in a fine-textured matrix or united by a brown ferruginous paste. The rock-fragments are of various quartz-porphyries and granophyres, and sometimes detached spherules; the crystals are of acid felspar and decomposed augite (near Llanbedrog, *etc.*)[1]. Dr Bonney[2] has described an agglomeratic type from the older rocks of the Llanberis district as consisting of fragments and lapilli of rhyolite and fragments of quartz and felspar embedded in an altered felspathic dust. Here some of the rock-fragments are of large size. Good rhyolite-tuffs, some with the characteristic micro-structure of broken pumice, occur among the 'Upper Ashes' of the Arenig district, and others have been described by Mr Cope[3] from Aran Mowddwy.

Rhyolite-tuffs are found also near Builth[4], at various places in Pembrokeshire (St David's[5], Fishguard[6], Llanrian), at Pontesford Hill in Shropshire[7], and near Malvern (Knighton). Some of these rocks (*e.g.* Builth and Llanrian, fig. 74, *A*) show well the broken-pumice structure already mentioned.

Some of the fine-textured rocks which have been styled 'porcellanite' and 'hälleflinta' are acid tuffs compacted by secondary silica and other substances. Examples occur in the St David's district (Clegyr Bridge, *etc.*) and in Charnwood Forest (Nanpanton). Rocks of the same general aspect in the Lake District (Bow Fell, *etc.*) are fine tuffs of intermediate composition.

A number of rhyolitic tuffs and breccias are described by Zirkel[8] from the Tertiary volcanic region of Nevada, while others occur among the ancient volcanic rocks of the eastern

1 *Bala Volc. Ser. Caern.*, 27.
2 *Q. J. G. S.* (1879) xxxv, 312.
3 *Pr. Liverp. G. S.* (1897) viii, pl. IV, V.
4 Rutley, *Q. J. G. S.* (1902) lviii, p. 30, with figure, and pl. II.
5 Geikie, *ibid.* (1883) xxxix, 297–301.
6 Reed, *ibid.* (1895) li, 175.
7 Boulton, *ibid.* (1904) lx, 474, 475, pl. XLIII, fig. 4.
8 *Micro. Petrogr. Fortieth Parallel* (1876) 264–271.

States[1]. Rhyolitic tuffs of Palæozoic age are known also in Australia[2], and Tertiary examples in the North Island of New Zealand[3].

Of *andesite-tuffs* some with the general composition of hornblende- and especially of mica-andesites, enclosing broken crystals and lapilli, occur in the Old Red Sandstone of the Oban district[4] (fig. 74, *B*). Tuffs of Ordovician age at Bail Hill, near Sanquhar in Ayrshire[5], contain abundant well-shaped

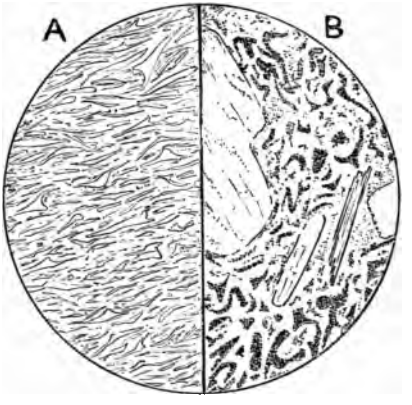

FIG. 74. ANCIENT PUMICEOUS TUFFS; × 20.

A. Rhyolitic Tuff (Ordovician), Llanrian, Pembrokeshire. Originally composed wholly of glass-fragments, the outlines of which are still partly discernible, despite their alteration [475].

B. Andesitic Tuff (Old Red Sandstone), Inverinan, Argyllshire. The outlines of many of the fragments are indicated, owing to their being charged with magnetite-dust. There are also partly rounded crystals of plagioclase and an occasional flake of biotite [2385].

1 See, *e.g.*, G. O. Smith, *Geology of Fox Island, Me.* (1896) 39 and pl. I, fig. 4.

2 Howitt, *Rep. Progr. Geol. Sur. Vict.* (1877) 78, 79, and (1878) 136–138, pl. II, figs. 7, 8 (N. Gippsland).

3 Sollas, *Rocks of C. Colville Peninsula*, vol. ii (1906) 15, 43, *etc.*, with plates.

4 Kynaston, *Tr. Edin. G. S.* (1901) viii, 87–90, pl. III.

5 Teall, *Ann. Rep. Geol. Sur.* for 1896, 39.

crystals of hornblende and augite, up to ¼ inch in length, and may be regarded as crystal-tuffs of the hornblende-andesite type. A rock with similar crystals occurring at Rhobell Fawr in Merioneth[1] is perhaps of more doubtful nature.

The pyroxene-andesites are much more widely represented in fragmental accumulations of various ages. To this type belong the ejectamenta of many of the most violent outbursts of modern volcanoes. The volcanic dust thrown out from Krakatau in the great eruption of 1883 has been described by several writers[2]. About nine-tenths of the material consists of glass fragments with the characteristic features noticed above. The remainder is of comminuted crystals of plagioclase, magnetite, enstatite, and augite, the whole having the composition of an acid pyroxene-andesite. Of quite similar nature was the volcanic dust from Mt Pelée[3] and from the Souffrière in St Vincent[4] (1902–3).

The majority of the Ordovician tuffs in the Lake District correspond in general composition with andesites and with basic andesites or basalts, but many of them have in addition angular fragments of rhyolite[5]. Crystals of felspar are often seen, but do not make up a large part of the rocks, which are essentially of the compact type in most cases (fig. 75). Rolled pieces of lava of small dimensions may occur. In some localities the rocks consist mainly of a mixture of small lapilli with fragments of slate, grit, *etc.*, often metamorphosed. Mr Hutchings has described an example from Falcon Crag near Keswick[6]. The finer tuffs of the district are often cleaved and highly altered (see below, p. 287).

The cleaved tuffs of Cader Idris[7] in Merioneth also contain plenty of slate-fragments with felspar crystals and particles of

[1] Cole, *G. M.* 1893, 343.

[2] Murray and Renard, *Nature* (1884) xxix, 585–589; Cole, *Proc. Geol. Ass.* (1884) viii, 332–335; Joly, *Proc. Roy. Dubl. Soc.* (1884) *N. S.* iv, 291–299, pl. XII, XIII; Judd, *Rep. Krak. Comm. Roy. Soc.* (1888) 38–41, pl. IV.

[3] Adye's *Stud. Micropetr.* 11, 12, pl. II, fig. 2.

[4] Flett, *Q. J. G. S.* (1902) lviii, 368, 369.

[5] Walker, *ibid.* (1904) lx, 95–98, pl. XIV, figs. 1, 2.

[6] *G. M.* 1891, 462.

[7] Cole and Jennings, *Q. J. G. S.* (1889) xlv, 423–431.

scoriaceous andesite-glass converted into green palagonite, all set in a fine ashy matrix. Fragments of shale occur also at some horizons in the important series of pyroclastic rocks in the Arenig district, which are for the most part of the nature of hypersthene-andesites[1]. Some other ancient tuffs consist largely of little fragments of formerly glassy and sometimes pumiceous andesite, now converted into a palagonite-like material of yellow or brown colour, as at Snead[2] and Pontesford Hill[3] in Shropshire. Tuffs consisting of lapilli and fragments of augite-andesite and andesitic pumice are found in the Arenig group at Llangynog, Caermarthenshire[4]; and others mainly of andesitic material have been described from the Bala group of Lambay Island, near Dublin[5].

FIG. 75. BASIC TUFF, ORDOVICIAN, WET SLEDDALE NEAR SHAP; × 20.

The bulk of the rock is of very fine particles, but encloses some rock-fragments and numerous crystals of felspar, which tend to stand perpendicularly to the lamination of the matrix [895].

[1] Fearnsides, *Q. J. G. S.* (1905) lxi, 623–626.
[2] Cole, *ibid.* (1888) xliv, pl. XI, fig. 5.
[3] Boulton, *ibid.* (1904) lx, 463–469, pl. XLII and XLIII, figs. 1, 2.
[4] Cantrill and Thomas, *ibid.* (1906) lxii, 241, pl. XXVI, fig. 1.
[5] Gardiner and Reynolds, *ibid.* (1898) liv, 140, 141; Sollas, *Pr. Geol. Ass.* (1893) 101, with figs. 7, 8.

Some interesting fragmental rocks of *basaltic* composition occur in the old volcanic series of St David's, of early Cambrian or pre-Cambrian age. They are agglomeratic tuffs, consisting chiefly of little fragments of basic lava, sometimes rounded but usually angular or subangular. In some there is very little matrix : it consists of fine *débris* of the same material as the larger fragments. Sir A. Geikie[1] has described specimens from Pen-y-foel and Pen-maen-melyn.

Among the basaltic rocks crystal-tuffs seem to be almost unrepresented. A common type consists of lapilli of basalt (glassy or altered) cemented by calcite, aragonite, limonite, *etc.* Widely distributed is the *palagonite* type of Waltershausen, described from Sicily, Iceland, the islands of the Pacific, *etc.* This consists chiefly of little fragments of altered

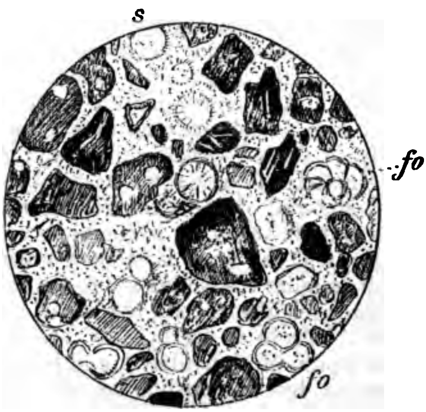

FIG. 76. CALCAREOUS TUFF, EUA, TONGA ISLANDS ; × 20.

The fragments are mainly of brown-stained andesitic and basic lava, more or less glassy and altered to palagonite. These, with tests of foraminifera (*fo*), are enclosed in a calcareous matrix. Each foraminiferal chamber is occupied by calcite with radial fibrous structure, giving a perfect black cross between crossed nicols, and the same is seen in the little spherical bodies (*s*), which are doubtless detached chambers of *Globigerina* [1273].

[1] *Q. J. G. S.* (1883) xxxix, 295–300, pl. IX, figs. 1, 2.

glassy basalt, usually of brown colour, often vesicular, and sometimes enclosing a few crystals of augite, olivine, or basic plagioclase ; while the cementing material is obtained from the decomposition of the fragments, or may include calcite derived from calcareous matter contemporaneously deposited or by infiltration from without (fig. 76). Palagonite-tuffs, as well as other basalt-tuffs, occur in Nevada, *etc.*[1]

Submarine tuffs of intermediate and basic composition occur, for example, abundantly in the Carboniferous in the basin of the Firth of Forth. Most of them contain some admixture of detrital or calcareous matter, but characteristic examples of tuffs, and in particular of palagonite-tuffs, are found. As described by Sir A. Geikie[2], the bedded deposits consist of a fine-textured matrix enclosing fragments of lava. The latter are the *débris* of already consolidated rocks rather than typical lapilli : they are largely vesicular, not only at the margin but throughout, and the vesicles are often cut by the external surface of the fragment. Calcite, delessite, *etc.*, occupy the cavities. A common feature is fragments of a transparent green or yellowish material resembling serpentine, which is evidently an altered vesicular glass, and is referred to palagonite. The matrix of these rocks has probably consisted of finely divided material of the same general nature as the larger fragments, but its structure is completely obscured by secondary changes, and the mass is stained green or brown. Tuffs of essentially similar characters are found in the Carboniferous of the Bristol neighbourhood[3], the Isle of Man[4], and the Limerick district[5]. Those in Derbyshire[6] are in great part composed of true lapilli, often bordered, and having numerous vesicles not broken by the outline of the lapillus. The material is a brown glass with globulites and crystallites and with crystals of olivine or plagioclase. These minerals are

[1] Zirkel, *Micro. Petr. Fortieth Parallel* (1876) 272–275, pl. XII, figs. 3, 4.

[2] *Trans. Roy. Soc. Edin.* (1879) xxix, 513–516, pl. XII, fig. 10.

[3] Lloyd-Morgan and Reynolds, *Q. J. G. S.* (1904) lx, 154, 155.

[4] Hobson, *ibid.* (1891) xlvii, 442, 443.

[5] Watts, *Guide*, 95.

[6] Arnold-Bemrose, *Q. J. G. S.* (1894) l, 625–642 ; pl. XXIV, figs. 4, 5, XXV.

often replaced by calcite, and the same substance fills the vesicles and forms the cement of the rock.

Fine-grained tuffs, and in a less degree agglomerates, may receive, as already mentioned, a secondary *cleavage-structure* precisely similar to that observed in argillaceous rocks; and the cleavage is often accompanied by mineralogical changes. The cleaved tuffs or ash-slates of the Lake District have been noticed by Dr Sorby, and some of them described in detail by Mr Hutchings[1]. These rocks are of intermediate, and sometimes perhaps basic, composition, and the finely divided portions have undergone great secondary changes. Chlorite and dust or granules of calcite are often conspicuous, and when these have been removed by acid from the powdered rock, or from very thin slices, other minerals may be detected, especially minute sericitic mica, which gives bright polarization-tints. The needles of rutile, so characteristic of clay-slates, are not found, but there are sometimes granules of sphene (*e.g.* Kentmere). In some of these slates minute garnets play an important part (*e.g.* Mosedale, near Shap). In general there has been an abundant separation of silica, partly as quartz, partly perhaps as chalcedony.

This is the general character of the finest slates of the Lake District, which are evidently greatly altered from their original state. The coarser bands have a matrix of similar character enclosing lapilli and recognizable fragments of andesite and also of rhyolite. Some rocks of a comparatively coarse agglomeratic nature are worked for slates in Borrowdale.

[1] *G. M.* 1892, 154–161, 218–228; see also *Pr. Liverp. G. S.* (1901) ix, 106–112, pl. VI, VII.

E. METAMORPHISM.

Using the term 'metamorphism' in a broad sense, we understand by it the production of new minerals, or new structures, or both, in pre-existing rock-masses. We must limit such a conception by supposing on the one hand that the changes produced are sufficient to give a distinctive new character to the rock as a whole, and on the other hand that they do not involve the loss of individuality of a rock-mass (*e.g.* bodily fusion must be excluded).

It is customary to distinguish *thermal* metamorphism, due to heat, and *dynamic* metamorphism, due to pressure. These can to some extent be considered separately, and we shall examine some of their results in the following pages. But, before doing so, we must notice that very important changes, which cannot reasonably be excluded from the domain of metamorphism, are set up in rock-masses without the intervention of either high temperature or great mechanical force. Many of these changes depend upon the access of circulating waters in communication with the atmosphere, and we may, if we please, roughly group them as meteoric or *atmospheric* metamorphism. In most cases, however, these processes involve some changes in the total composition of the rocks affected, either a loss of some constituents or an addition of others (water, oxygen, carbonic acid, and other substances): in other words there is often *metasomatism* as well as metamorphism.

The common weathering-products of igneous rocks are results of such processes, but it is convenient, as already

remarked, to restrict the term metamorphism to cases in which the general mass of a rock is considerably altered : the serpentine-rocks are an example. It is important to observe, however, that the minerals produced by secondary actions of the kind here contemplated include some which are also common as original constituents of igneous rocks. We have already mentioned the occurrence in this way of secondary quartz, felspars, hornblende, *etc.* There is a frequent tendency of the new-formed substance to form as a crystalline extension of pre-existing crystals or grains of the same mineral (*e.g.* the quartz in many quartzites); or again for a pre-existing mineral to be extended by an outgrowth of some allied mineral with the same crystalline orientation : *e.g.* one kind of plagioclase felspar may receive an extension of another kind, augite of hornblende, allanite of epidote.

The most striking examples of what we have termed atmospheric metamorphism and metasomatism are found among the sedimentary rocks. We have already remarked the conversion of sandstones to quartzites, the recrystallization of limestones and their replacement by dolomite, iron-compounds, silica, *etc.*, and we have seen that very many argillaceous sediments have undergone extensive or almost complete reconstitution since they became strata.

More remarkable is the evidence of the formation of crystalline schists on an extensive scale by metasomatic changes alone, described by Prof. Van Hise in the Lake Superior region. In the upper part of the Penokee Iron-bearing Series[1] of Michigan and Wisconsin felspathic grits, greywackes, *etc.*, are traced into finely crystalline mica-schists, with biotite and muscovite, all relics of the clastic structure being finally obliterated. In the lower members of the same series[2] rocks consisting of impure carbonates mixed with chert have been converted into ferruginous quartz-schists, magnetite- and hæmatite-schists, magnetite- and hæmatite-bearing actinolite-schists, *etc.*, also by metasomatic processes (silicification and

[1] Van Hise, *A. J. S.* (1886) xxxi, 453–459; Irving and Van Hise, *Penokee Iron-bearing Series* in 10*th Ann. Rep. U. S. Geol. Sur.* (1890) 423–435, pl. XXXVIII–XLII.

[2] Van Hise, *A. J. S.* (1889) xxxvii, 32–47; Irving and Van Hise, *l.c.* *Cf.* Hudleston, *Pr. Geol. Ass.* (1889) xi, 133–138.

other replacements), apparently without the conditions for either thermal or dynamic metamorphism. Similar rocks occur in the Mesabe range, Minnesota[1].

We may now pass on to such changes affecting rock-masses as are more usually understood by the term metamorphism as employed in text-books. The changes are in part *mineralogical* (in most cases without any very important metasomatism), in part *structural*. These two lines of change are so connected that they cannot be considered quite separately: roughly we may say that mineralogical modifications are the more prominent in thermal metamorphism, and structural in dynamic.

While treating in turn the chief features of thermal and of dynamic metamorphism, we must remember that their effects may be associated or superposed in the same area, and the assigning of particular mineralogical changes to one or the other cause is in many cases still a question for discussion.

[1] Bayley, *A. J. S.* (1893) xlvi, 176.

CHAPTER XX.

THERMAL METAMORPHISM.

UNDER this head we include all changes produced in pre-existing rock-masses by the influence of high temperature. In the simplest case this is brought about by the intrusion of an igneous magma in the neighbourhood ('contact' or 'local' metamorphism of many authors); but we must also include the effects of heat mechanically generated (thermal being then associated with dynamic phenomena), and those due to the internal heat of the Earth in a rise of the isogeotherms. These latter especially may affect rock-masses on a regional scale. We shall here avoid complication by drawing our examples, so far as is possible, from cases of thermal metamorphism produced by igneous intrusions.

Characteristic minerals. It will be convenient to refer briefly to the commoner minerals formed in thermal metamorphism, some of them being unknown or rare in igneous rocks. *Quartz* and felspars are widely distributed in metamorphic rocks of various kinds. The felspars include *orthoclase*, *albite*, *anorthite*, and various intermediate members of the plagioclase series. They are often perfectly clear, and when they occur as minute shapeless granules in a mosaic they may easily be mistaken for quartz without special optical tests[1]. The larger grains show cleavage and sometimes characteristic twinning or some approach to crystal outline.

[1] Becke has given a staining method, using aniline blue after etching with hydrofluoric acid. Plagioclase is deeply coloured, orthoclase only slightly affected, and quartz unchanged (for examples see Berwerth, *Lief.* III).

Both *muscovite* and *biotite* are found in metamorphosed rocks, the latter being very widely distributed. It is apparently a haughtonite and always strongly pleochroic, with a deep reddish-brown colour or, for vibrations parallel to the cleavage-traces, a very deep brown with a noticeable greenish tone. Intensely pleochroic haloes surround certain inclusions. Less usual than brown mica as a conspicuous mineral is a green *ripidolite* or a yellowish or greenish *chlorite*. In the fine-textured 'base' of argillaceous rocks, however, Mr Hutchings[1] notes that the conversion of impure micaceous material into an aggregate of muscovite and chlorite, so characteristic in the passage of clays and shales into slates, is also met with in thermal metamorphism, especially where there is no abundant production of biotite. Exceptionally we find the manganese-bearing chloritoid mineral *ottrelite*[2] (fig. 80, *A*). It builds flakes without special orientation, and freely encloses impurities: the lamellar twinning parallel to the base and a modification of hour-glass structure are noticeable[3].

Highly characteristic of the metamorphism of argillaceous and some other rocks are silicates rich in alumina. *Andalusite* forms more or less idiomorphic crystals with the prism-form and usually some traces of the prismatic cleavage. It is recognized by its moderately high refractive index with low double refraction (about the same as in labradorite) and straight extinction. When it shows any colour, it is pleochroic, giving a rose tint for longitudinal and a very faint green for transverse vibrations. It may be quite clear, or may contain numerous inclusions, certain enclosed minerals being surrounded by a pleochroic halo (bright yellow to colourless). In *chiastolite*[4] the elongated crystals contain a large amount of foreign matter, apparently carbonaceous, arranged in the fashion peculiar to the mineral (fig. 79). *Sillimanite* (*fibrolite*) builds elongated prisms or needles, which in shape, cross-fracture[5], and refractive index resemble apatite, but have a

[1] *G. M.* 1896, 344, 345; 1898, 74, 75.

[2] See Hutchings, *G. M.* 1889, 214; Whittle, *A. J. S.* (1892) xliv, 270–277.

[3] Cohen (3), pl. XXII, fig. 4; XXX, fig. 3.

[4] *Ibid.* pl. XVII, fig. 4.

[5] *Ibid.* pl. XLVII, fig. 2.

much stronger birefringence (fig. 77). They are often crowded together in matted aggregates embedded in quartz ('Faserkiesel' or 'quartz sillimanitisé'[1]). *Cyanite*[2] or disthene is found less commonly, building more or less rounded crystals or grains, with pinacoidal cleavage and a cross-fracture corresponding with a gliding-plane. In thin sections it is colourless or pale blue, with pleochroism, and, owing to its high refractive index, shows a strong relief. Longitudinal sections give extinction-angles up to 31°. *Staurolite* forms good crystals, the larger ones always crowded with various inclusions (fig. 86)[3]. When fresh, it is yellowish or reddish-brown with distinct pleochroism[4] and strong refringence and birefringence. This mineral, however, and in varying degree all the aluminous silicates, are very liable to decomposition, the characteristic product being white mica in minute scales (the 'shimmer-aggregate' of Barrow[5]). *Cordierite* is sometimes less easily recognized. It is commonly in shapeless grains crowded with inclusions, but sometimes builds pseudo-hexagonal prisms, basal sections of which occasionally show the curious triple twinning[6]. The mineral rarely shows its colour and pleochroism in thin slices, but is sometimes stained of a yellow tint. The refractive index and double refraction are low.

The metamorphism of calcareous rocks gives rise to numerous silicates rich in lime, or in lime and magnesia. The pure lime-silicate *wollastonite* is colourless in thin slices, and shows lower refringence and birefringence than the augites. It is further distinguished by having its two principal cleavages and its direction of elongation perpendicular to its plane of symmetry, and consequently giving straight extinction. As a rule, it occurs in quite small imperfect crystals. The augites of metamorphosed limestones, *etc.*, are either non-aluminous (*diopside*) or aluminous (*omphacite*). They build imperfect

[1] Cohen (3), pl. xxxvii, fig. 3; Williams, *A. J. S.* (1888) xxxvi, pl. vi, figs. 2, 4; Barrow, *Q. J. G. S.* (1893) xlix, 338, pl. xvi, figs. 1, 2.
[2] Cohen (3), pl. xlii, fig. 4; Barrow, *l.c.* 338, 339, pl. xvi, figs. 3, 4.
[3] Williams, *A. J. S.* (1888) xxxvi, pl. vi, fig. 3. On arrangement of inclusions see Penfield and Pratt, *ibid.* (1894) xlvii, 81–89.
[4] Cohen (3), pl. xxvii, fig. 1.
[5] *Q. J. G. S.* (1893) xlix, 340, pl. xvi, fig. 5.
[6] Cohen (3), pl. xxix, fig. 3.

crystals or crystalline patches, take part in a finely granular mosaic, or occur as little globules enclosed in other minerals. The crystals are occasionally twinned on the usual law. The green colour is often imperceptible in thin slices. Both diopside and omphacite give extinction-angles of 38° or 40°, and it is not always possible to discriminate between them, though the former is sometimes betrayed by its partial conversion into serpentine. The most common amphibole in these rocks is a colourless *tremolite* in imperfect crystals, crystalline patches, veins, or sheaf-like groupings. It may show a fibrous structure or a good hornblende-cleavage, and a rough cross-fracture is also common. Green *hornblende* and blade-like *actinolite* are found in some rocks. The lime-garnet *grossularite* forms well-bounded crystals, often of considerable size, with included pyroxene granules (fig. 82). It is often feebly birefringent, and further shows between crossed nicols a polysynthetic twinning of a remarkable kind[1]. With this structure goes a strongly marked zonary banding, the concentric zones differing in birefringence. *Idocrase* occurs either in well-built crystals or in shapeless plates enclosing other minerals. The cleavage and colour are usually not to be observed in thin sections. The birefringence is variable, and a crystal often shows bands or lamellæ differing in interference-colours. *Zoisite* occurs in little prisms, often grouped in sheaf-like fashion. It is characterized by longitudinal cleavage-traces, high refractive index, low polarization-tints, and straight extinction. *Epidote*, often associated with the last-named mineral, is usually in shapeless grains or granular aggregates, though it may present crystal-boundaries towards calcite, *etc.* The cleavages are well-marked, the two sets of traces intersecting at about 65° in a cross-section. Twinning is uncommon. The larger crystals show the yellow colour and pleochroism. Other distinctive characters are the high refractive index, very brilliant polarization-tints, and straight extinction in longitudinal sections.

A characteristic mineral in metamorphosed dolomite-rocks is the pure magnesian olivine *forsterite*. It forms either crystals of tabular habit (fig. 83) or rounded grains, and by

[1] Cohen (3), pl. LII; also, for numerous figures, Klein, *Neu. Jahrb.* 1883, i, pl. VII–IX.

alteration gives rise to serpentine. In certain cases magnesia has crystallized in the form of *periclase*, in octahedra or in rounded grains (*e.g.* in the ejected blocks of Monte Somma, Vesuvius); but this passes readily by hydration into *brucite*, a clear, colourless mineral with one (basal) cleavage, straight extinction with the cleavage-traces, low refringence, and strong birefringence (nearly equal to that of augite).

Among other products of thermal metamorphism in various rocks may be mentioned common garnet, chloritoid, dipyre, magnetite and ilmenite, pyrite and pyrrhotite, sphene, rutile and anatase, spinels, corundum, and graphite. Further, the formation of a certain amount of isotropic matter is recorded in some cases[1].

As a special mineral formed in metamorphosed rocks near an igneous intrusion may be noticed *tourmaline*. This mineral occurs in little grains, often in veins which represent cracks, or sometimes very abundantly as a constituent of a kind of contact-breccia. It is restricted to the neighbourhood of acid intrusions, and depends on an actual introduction of certain materials from the igneous magma. White mica has sometimes a similar occurrence; and processes of the same order (pneumatolytic metamorphism), operating on impure limestones, have in some cases given rise to *axinite*.

Metamorphism of arenaceous rocks. The effects of thermal metamorphism in arenaceous rocks are simple or complex according to the homogeneous or heterogeneous nature of the deposits affected. In a pure quartz-sandstone or quartzose grit there are no degrees of metamorphism possible. If the temperature be sufficiently high, the whole will be recrystallized into a clear quartz-mosaic without a trace of the original clastic character. Short of this change, the sandstone will be unaltered, except in such minor points as the expulsion of the water from the fluid-pores of the quartz, an effect noticed by Sorby at Salisbury Crags. The homogeneous quartzite resulting from the complete metamorphism of a pure quartzose rock is not difficult to discriminate from a quartzite formed by the deposition of interstitial quartz. There is no distinction of

[1] On this and some other points see Hutchings, *G. M.* 1894, 36–45, 64–75.

original grains and cementing material, no secondary growth upon original nuclei, but each element of the mosaic is clear and homogeneous, presenting an irregular boundary which fits into the inequalities of the adjoining elements. Such quartzites are locally produced in the Skiddaw grits abutting on the large granophyre mass at Ennerdale, in the Carboniferous sandstones near the Whin Sill of Teesdale, and in many other places. If the original sediment contained felspar grains, not much altered, as well as quartz, the felspar is recrystallized with the quartz, and without careful examination is liable to be overlooked in the resulting mosaic.

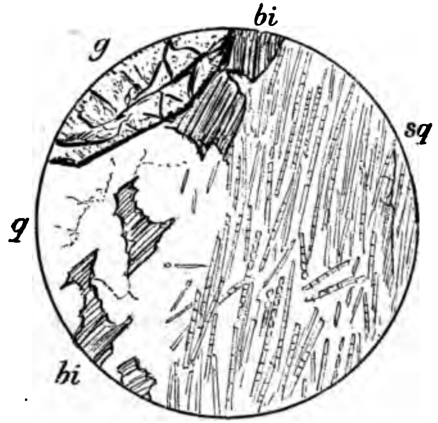

FIG. 77. GARNET-SILLIMANITE-SCHIST OR GNEISS, A HIGHLY METAMORPHOSED GRIT, CLOVA, FORFARSHIRE ; × 20.

The right half of the figure shows an area of clear quartz full of little prisms of sillimanite with characteristic cross-fracture (*sq*) : to the left are clear quartz (*q*), biotite (*bi*), and part of a large garnet (*g*) [1808].

The metamorphism of a specially pure type of siliceous rock has been described by Dr Horne[1] in the case of the Arenig radiolarian cherts of the south of Scotland, as they approach the Loch Doon granite. The final result is a mosaic of

[1] *Rep. Brit. Ass.* for 1892, 712. *Cf. Ann. Rep. Geol. Sur.* for 1896, 46, and Teall, *Mem. Geol. Sur., Silur. Rocks Scot.* (1899) 640–642.

granular quartz with numerous minute round inclusions of biotite.

Where a quartzose sandstone or grit has contained scattered decomposition-products, such as kaolin, calcite, and chloritic minerals, in small quantity, metamorphism produces a quartzite with granules of some accessory mineral. Thus, near the Shap granite, the grits in the Coniston Flags group have been transformed into a quartzite with granules of colourless pyroxene, formed from kaolin and calcite. Similarly the chloritic minerals give rise to brown mica. A curious green mica occurs in the quartzite of Clova in Forfarshire.

If the original rock was more impure, containing more of aluminous and other substances, the product of metamorphism ceases to have any apparent resemblance to a quartzite. Silicates of alumina, garnet, micas, *etc.*, may be extensively produced, and the metamorphosed rock assumes the aspect of a fine or even a coarse gneiss (fig. 77). Remarkable examples are presented by the Silurian grits and flags round the Old Red Sandstone granites of Galloway[1]. Here the chief constituents are quartz, muscovite, a deep brown biotite, and red garnet (colourless in slices), felspar being only subordinate. The garnets, except at the margin of each crystal, are crowded with minute granular inclusions : they tend to occur in clusters moulded by clear quartz, a frequent association in many metamorphic rocks. Nearer to the granite the texture of the rock becomes coarser, and the muscovite and quartz are seen to be crowded with narrow needles of sillimanite up to ·01 inch long. The same minerals as before are present, with a few crystals of plagioclase and rarely a little brown tourmaline. At a hundred yards from the granite margin the texture is very coarse, the abundant white mica building plates half an inch in length and relatively thick. Dense matted aggregates of sillimanite needles occupy the interior of the quartz and muscovite, leaving the borders of the crystals clear. Some of the most altered rocks show bands or streaks rich in particular minerals, such as lenticular patches of garnet set in clear

[1] Miss Gardiner, *Q. J. G. S.* (1890) xlvi, 569–580; Teall, *Mem. Geol. Sur., Silur. Rocks Scot.* (1899) 644–647.

quartz or streaks composed essentially of muscovite and sillimanite, dark mica being less plentiful (fig. 78).

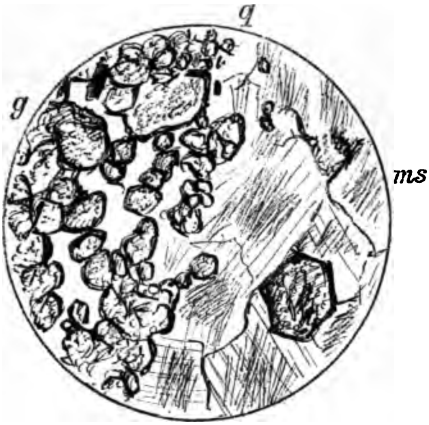

FIG. 78. GARNET-SILLIMANITE-SCHIST OR GNEISS, A HIGHLY METAMORPHOSED GRIT, KNOCKNAIRLING HILL, NEW GALLOWAY; × 20.

The figure shows portions of two lenticular streaks, one consisting essentially of muscovite crowded with minute needles of sillimanite (*ms*), the other of garnet (*g*) set in clear quartz (*q*) [1173].

Some highly metamorphosed sediments in the eastern Highlands of Scotland are rich in cordierite, usually crowded with inclusions of other minerals and having round certain inclusions the characteristic pleochroic yellow haloes. An example from the Buck of Cabrach in Banffshire consists of cordierite and white mica in allotriomorphic crystals and a mosaic of microcline with some quartz, andalusite, magnetite, and biotite. This rock has a massive structure, but others in the same district are gneissose and schistose[1]. Corundum, as well as sillimanite, spinel, *etc.*, occurs in some of these cordierite-bearing rocks[2].

[1] Teall, *Mem. Geol. Sur. Scot., Expl. Sheet* 75 (1896) 36, 37, 45; and *Ann. Rep. Geol. Sur.* for 1896, 18, 19.

[2] Teall, *Summary of Progress Geol. Sur.* for 1898, 86–88; *Pr. Geol. Ass.* (1899) xvi, 63, 64 (Monadh Driseag near Loch Awe).

Some of the Scottish rocks cited, with relatively coarse texture due to extreme thermal metamorphism, and a more or less pronounced banded structure representing bedding, afford good examples of *gneisses* formed by the metamorphism of sedimentary deposits. Rosenbusch terms such rocks 'para-gneisses,' as distinguished from 'orthogneisses' which are of igneous origin. He further uses the names 'psammite-gneiss' and 'pelite-gneiss' for types arising from the metamorphism of arenaceous and argillaceous sediments respectively. Again, having regard to the characteristic minerals present, we may distinguish sillimanite-gneiss, andalusite-gneiss, cordierite-gneiss, *etc.*

Metamorphism of argillaceous rocks. The effects of thermal metamorphism in clays, shales, or slates depend in the early stages of alteration on the mineralogical, and in the later stages on the chemical, composition of the rocks affected.

In strata containing carbonaceous matter this is one of the first ingredients to suffer change. It is either dissipated and expelled or converted into graphite. The latter is in some cases aggregated into little dark spots, producing one type of what is known as 'spotted slate' (Ger. Knotenschiefer). This peculiarity may be seen in otherwise unaltered strata, and it disappears with advancing metamorphism. The minute needles of rutile so abundant in slates also seem to be rather readily affected, giving place to stouter crystals of the same mineral, or less commonly to anatase or brookite. Another early effect of metamorphism is the production of little flakes of brown mica (probably the haughtonite variety of biotite) from chloritic substances, *etc.* With this there may be a crystallization of iron-ores (magnetite or pyrites). In some cases a chloritic mineral or ottrelite is formed instead of the mica. In rocks rich in alumina chiastolite is produced concurrently with biotite[1], *e.g.* in the Skiddaw district (Bannerdale, Roughton Gill, *etc.*, fig. 79).

With advancing metamorphism graphitic spots and chiastolite-crystals are lost, and the metamorphism begins to affect

[1] For good coloured figures see Teall, pl. XXXIII, fig. 2 (Skiddaw); Fouqué and Lévy, pl. III, fig. 1 (Brittany).

the whole body of the rock, the chief products formed being usually quartz and biotite. Of these the latter often has its flakes oriented in accordance with the original lamination or cleavage of the rock, and we have thus one type of mica-schist (Ger. Glimmerschiefer). These rocks may have no trace of

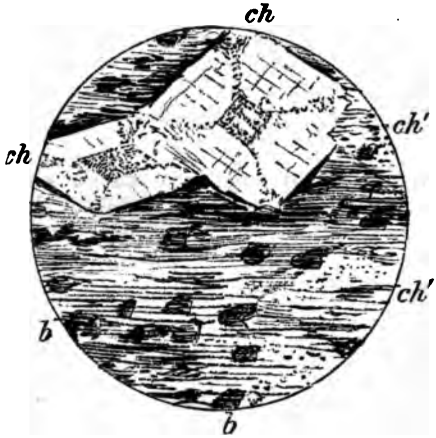

FIG. 79. CHIASTOLITE-SLATE, SKIDDAW SLATE METAMORPHOSED BY GRANITE, BANNERDALE, SKIDDAW; × 20.

Besides good cross-sections of chiastolite (*ch*), showing the characteristic arrangement of enclosed impurities, there are imperfectly developed crystals (*ch'*) clearly detected by using polarized light. In the general mass of the rock the chief metamorphic effect is the production of little flakes of biotite (*b*) [1111].

the original clastic nature of the deposit, except perhaps some minute angular quartz-grains. They sometimes show a spotted character quite different from that mentioned above, and consisting in little ovoid spaces free, or relatively free, from the flakes of biotite which crowd the rest of the rock. Such spaces often show distinctly crystalline properties, giving extinction parallel with their length, and in many cases, at least, they are ill-developed crystals of andalusite or of cordierite.

In the highly metamorphosed Skiddaw Slates of the Caldew Valley, *etc.*[1], cordierite and andalusite, severally or together, are very abundant. The other common minerals are biotite, muscovite, and in the more siliceous beds quartz; while graphite is usually present, and chlorite, ilmenite, and minute garnets are found in particular beds. When the cordierite occurs in distinct crystal-grains, it gives the well known 'spotted' appearance, which is also produced in the same way in the metamorphosed Coniston Flags near the Shap granite[2] (fig. 80, *B*). In the Skiddaw Slates these imperfect crystals of cordierite are often complex twins. When, however, the mineral constitutes the chief bulk of the metamorphosed rock, it forms a sort of ground-mass of irregular grains, fitting together and enclosing the biotite and other minerals. The spotted character is thus lost.

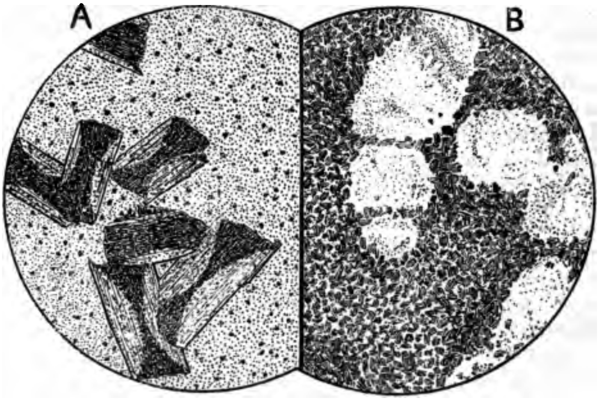

FIG. 80; × 20.

A. Ottrelite-slate (metamorphosed Cambrian slate), Ottré, Ardenne, Belgium. Crystals of ottrelite crowded with inclusions [1565].

B. Cordierite-Mica-schist (metamorphosed Coniston Flags), near Shap granite, Wasdale Beck, Westmorland. The ovoid spaces free from biotite indicate imperfect crystals of cordierite [866].

[1] *Naturalist*, 1906, 121–123, pl. x, xi; *G. M.* 1894, 169 (cordierite).

[2] Hutchings, *G. M.* 1894, 65. *Cf.* Harker and Marr, *Q. J. G. S.* (1891) xlvii, 320, pl. xii, fig. 5.

The slates near the Leinster granites are in part converted into mica-schists with staurolite and graphite. Locally they show spots, which develop into crystals of andalusite, sometimes of considerable size (Killiney, near Dublin).

Various types of spotted and flecked rocks due to metamorphism have been styled spilosite, Fleckschiefer, Fruchtschiefer, Garbenschiefer, *etc.*, and show spots and patches of very various dimensions. In some they are evidently ill-formed crystals (*e.g.* cordierite); in others the true nature of the spots is not very clearly understood. Dr Teall[1] compares with the typical 'spilosite' of the Harz some slates near Tremadoc altered by large sheets of dolerite. Here the spots are almost invisible in a slice viewed in ordinary light, but become conspicuously dark between crossed nicols. This seems to be due to numerous minute overlapping scales of chlorite. A micaceous mineral occurs more sparingly, and an aggregate of granules having the refraction and double refraction of quartz and felspar. Similar phenomena are seen in other parts of North Wales, *e.g.*, near the granite of Ffestiniog, and in many other countries[2]. Other metamorphosed slates near Tremadoc have a banded rather than a spotted character, thus answering to the 'desmoisite' rather than the 'spilosite' of the Harz geologists.

In extreme cases of metamorphism the rocks lose all spotted, and frequently all banded and schistose, structures, passing sometimes into an extremely compact, fine-textured mass of quartz, micas, iron-ores, *etc.* (Ger. Hornfels, Fr. cornéenne, 'hornstone' of some writers). Andalusite, garnet, *etc.*, characterize different types (Ger. Andalusithornfels, Granathornfels, *etc.*). Some highly metamorphosed strata, however, have a marked schistose character, usually due to micas of sericitic habit following old structural planes in the rock. Dark mica usually predominates, but white is also frequent. Red garnet is common in mica-schists of this kind, and other minerals may occur, according to the original chemical composition of the rock. A well-marked zone of

[1] *Brit. Petr.* 218.

[2] Clements describes a rock of this type in metamorphosed Huronian slates near Mansfield, Mich.; *A. J. S.* (1899) vii, 86.

graphitic mica-schists is known in the Central Highlands, and shows the characters of a thermally metamorphosed rock (fig. 81). The graphite doubtless represents carbonaceous matter of organic origin.

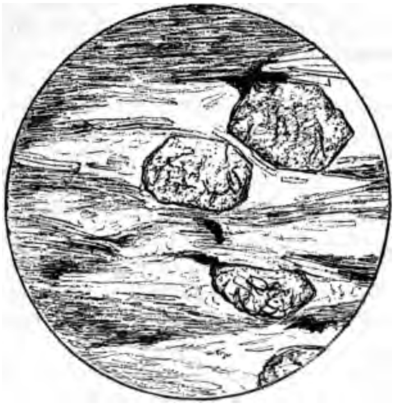

FIG. 81. GRAPHITIC MICA-SCHIST, BLAIR ATHOLL, PERTHSHIRE; CUT PERPENDICULARLY TO THE SCHISTOSITY; × 20.

The rock consists mainly of quartz and sericitic mica, with some finely divided graphite. There are also numerous dodecahedra of garnet, each in the centre of a lenticular streak or 'eye' of quartz [1834].

In slates which originally contained a considerable amount of muscovite or of finely divided felspathic matter, or at least had not become much impoverished in alkalies, the phenomena of metamorphism are somewhat different from those sketched above. Chiastolite is not formed, and andalusite does not usually figure largely in the more metamorphosed rocks, while new-formed white mica occurs abundantly with the biotite or to its exclusion. A good example of the type characterized by white mica is afforded by the slates of Charnwood Forest near a granitic intrusion at Brazil Wood[1]. Here the ragged flakes of muscovite enclose subordinate biotite with parallel intergrowth: a chlorite is also present, besides clear quartz

[1] Bonney, *Q. J. G. S.* (1877) xxxiii, 783. These slates are probably composed in great part of volcanic material.

and granules of opaque iron-ore. Near the Whin Sill of Teesdale Mr Hutchings[1] finds the Lower Carboniferous shales converted in some beds to a minute aggregate wholly of muscovite and chlorite. An example of extreme thermal metamorphism is afforded by the Silurian shales near the New Galloway granite[2]. The rocks consist of quartz, light and dark micas, the former predominating, red garnet, and subordinate felspar. The mica gives a foliated character to the mass, and the quartz tends to aggregate in little knots or lenticles.

A very important feature in the metamorphism of many argillaceous rocks is the abundant new formation of felspars. This is probably a quite common occurrence in the advanced stages of metamorphism, but very careful study is needed to distinguish the felspar from quartz when it occurs in a minutely granular mosaic. Good instances are furnished by the Coniston Flags near the Shap granite. In shales near the Whin Sill of Teesdale, Mr Hutchings[3] finds spherical aggregates of quartz and felspar fibres.

In many cases of true contact-metamorphism, material introduced into the metamorphosed rocks from an invading magma has given origin to special minerals not dependent on the nature of the strata affected. The commonest of these special minerals is tourmaline. It has been formed abundantly in many of the slates bordering the granitic intrusions of Cornwall[4] and Devon. Besides the brown or blue tourmaline, the metamorphosed rocks consist of quartz, micas, chlorite, andalusite, *etc.* Some of the less altered slates have a spotted character in which the spots are imperfect crystal-grains of andalusite. The more altered rocks are mica-schists.

In the neighbourhood of some basic intrusions there seems to have been more important metasomatic change, brought about especially by a transference of soda from the magma to the rocks undergoing metamorphism. Some of the 'adinoles' of the Harz are ascribed to this action. They consist essentially of a fine-textured mosaic of quartz and albite with

1 *G. M.* 1896, 348–350; 1898, 74–77, 125–128.

2 Miss Gardiner, *Q. J. G. S.* (1890) xlvi, 570–573.

3 *G. M.* 1895, 124.

4 Allport, *Q. J. G. S.* (1876) xxxii, 408–417; Flett, *Mem. Geol. Sur., Geol. Land's End* (1907) 20–26.

sometimes other minerals. Dr Teall[1] compares with adinole a rock at Y Gesell near Tremadoc, which has the same mineral composition, with the addition of minute scales of mica and chlorite. In an adinole near a dolerite intrusion in the Huronian slates of Mansfield, Michigan, more than half the rock consists of albite, the other chief constituents being actinolite and quartz[2]. As an example apparently of a like transformation in arenaceous and even siliceous rocks, we may note a case on Angel Island, San Francisco, where, according to Ransome[3], not only felspathic sandstones but even radiolarian cherts are converted to glaucophane-schists, composed of quartz, albite, glaucophane, biotite, *etc.*

Metamorphism of calcareous rocks. It appears that, under the conditions which rule in ordinary cases of metamorphism by heat, carbonic acid is not driven off from lime-carbonate, except in presence of available silica to replace it. Thus a pure limestone is not altered in chemical composition by metamorphism. It is, however, at a sufficiently high temperature, recrystallized into a fine- or coarse-grained marble, in which all traces of clastic and organic structures are effaced. This is seen locally in the Mountain Limestone against the Whin Sill of Teesdale, in the purer parts of the Coniston Limestone near the Shap granite, *etc.*

Most metamorphosed limestones, however, have held sufficient impurities to give rise to various lime-bearing silicates, which are found in the recrystallized limestones as crystals, crystalline aggregates, patches, plumose tufts, *etc.* The chief characteristic minerals have been noted above. Two or more of them often occur in association, and sometimes with a regular arrangement. Thus some beds of the Coniston Limestone near the Shap granite enclose large crystals of idocrase in stellate groups or nests, each nest surrounded by a shell composed largely of felspar. Metamorphosed limestones in Glen Derry, near the Cairngorm granite, contain aggregates of garnet. In the Glen Tilt rocks we find chiefly amphibole-

[1] *Brit. Petr.* 219–221.
[2] Clements, *A. J. S.* (1899) vii, 87, 88.
[3] *Bull. Geol. Dep. Univ. Cal.* (1894) i, 212–219, 223–226; pl. XIII, figs. 3, 4.

minerals—tremolite, actinolite, and green or even brown hornblende. A band of crystalline limestone near Tarfside, in the highly metamorphosed area of Forfarshire, has green hornblende, zoisite, felspar, quartz, sphene, and other minerals. Fine examples of the production of lime-silicates (wollastonite, scapolite, felspars, pyroxenes, *etc.*) are furnished by the crystalline limestones bordering the gabbros of the Adirondacks and the Lake Champlain district[1]. Crystalline limestones with accessory minerals of metamorphic origin may attain a considerable development in areas of 'regional' metamorphism. The 'cipollino' of the Italian geologists is a rock of this kind containing mica and other silicates.

The most striking effects, however, are produced in very impure limestones or in calcareous shales, slates, or tuffs. In these the carbonic acid is completely eliminated, and the whole converted into a *lime-silicate-rock* (the German 'Kalksilikathornfels' or 'Kalkhornfels'). It appears too that quite a moderate amount of calcareous material in shales, tuffs, *etc.*, suffices to make the metamorphism take this line instead of those described under the head of argillaceous rocks. The metamorphosed rocks consist of aggregates, usually but not always fine-grained and compact, of silicates rich in lime with sometimes quartz, pyrites, or other minerals. Several of these minerals occur in association, giving rise to rocks of complex constitution; and beds differing slightly in the amount and nature of their non-calcareous material result in different mineral-aggregates. Numerous types are illustrated by the metamorphosed Coniston Limestones at Wasdale Head, where they abut on the Shap granite. The Upper Coniston Limestone is extensively converted into a compact porcellanous-looking rock, in which irregular crystalline patches and grains of pyroxenes and other lime-bearing silicates are recognizable. In some specimens wollastonite predominates, in others augite (omphacite), in others tremolite; and various associations of these and other minerals can be noted in thin slices[2]. Anorthite and probably other felspars are present, sometimes

[1] Kemp, *Bull. Geol. Soc. Amer.* (1894) v, 223; (1895) vi, 241–262; C. H. Smyth, jr., *ibid.* 263–284.

[2] Harker and Marr, *Q. J. G. S.* (1891) xlvii, pl. XII, figs. 3, 4.

in irregular crystal-plates or patches with ophitic habit, sometimes in minute granules. In the compact rocks are sometimes enclosed stellate groups of large crystals (idocrase or augite), each group surrounded by a shell chiefly of plagioclase crystals[1]. A bed in the Lower Coniston Limestone is converted into a mass of garnet and idocrase. The garnet (grossularite) is in good crystals enclosing pyroxene-granules and enclosed by the clear idocrase[2] (fig. 82). It shows the optical anomalies noted above[3]. A considerable variety of lime-silicate-rocks is found in the Cromdale Hills, *etc.*, in the eastern Highlands of Scotland[4].

FIG. 82. GARNET-IDOCRASE-ROCK (METAMORPHOSED CONISTON LIMESTONE), NEAR SHAP GRANITE, WASDALE HEAD, WESTMORLAND; × 20.

The highly refringent crystals are the lime-garnet (grossularite) and the clear mineral forming the matrix is idocrase. Both enclose abundant pyroxene-granules [2730].

More remarkable effects are produced when there has been an introduction of boric acid into the rock during the metamorphism. At South Brent, on the border of the Dartmoor granite, Busz has remarked a Devonian limestone

[1] Harker and Marr, *Q. J. G. S.* (1893) xlix, pl. XVII, fig. 6.
[2] *Ibid.* (1891) xlvii, pl XII, fig. 1.
[3] *Ibid.*, p. 312.
[4] Teall, *Mem. Geol. Sur. Scot., Expl. Sheet* 75 (1896) 36, 44.

converted into an aggregate of birefringent garnet and interstitial datolite. Axinite is another mineral occurring in like connexion. Mr Barrow[1] has found it, with actinolite and other minerals, in a metamorphosed Devonian limestone at Tregullon, near Bodmin, Cornwall.

Of special interest is the *dedolomitization* of dolomite-rocks by metamorphism. Here the dolomite is reduced to calcite, while its magnesia enters into new minerals. One well-marked type arising in this way consists of calcite and forsterite (fig. 83), and such a rock may be converted into a

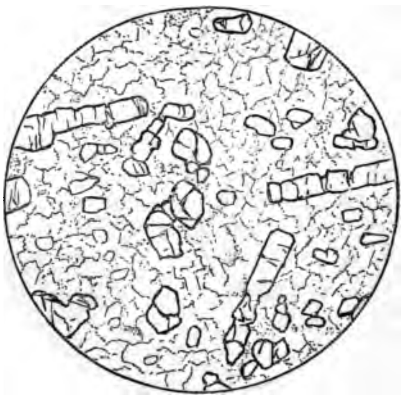

FIG. 83. FORSTERITE-MARBLE (METAMORPHOSED CAMBRIAN DOLOMITE), NEAR GRANITE, KILCHRIST, SKYE; × 20.

Showing crystals of olivine (forsterite) in a calcite-mosaic [2398].

serpentinous marble or 'ophicalcite.' Even a pure dolomite-rock, free from siliceous or other impurity, may be dedolomitized; and in this way have been formed the rocks known in the Tirol as 'predazzite' and 'pencatite,' which are granular aggregates of calcite and brucite[2], the latter probably arising from the hydration of periclase. These and other types are found among the metamorphosed equivalents of the Cambrian

[1] *Summary of Progress Geol. Sur.* for 1905, 32, 33.
[2] See Cohen (3), pl LXVI, fig. 1.

dolomite-rocks at Ledbeg in Sutherland, on the border of the Loch Borolan intrusion[1], and also in Skye[2], where the same group of strata is highly metamorphosed by the Tertiary granite and gabbro. The crystalline limestones of Glenelg[3], Tiree[4], and Iona carry a variety of minerals, among which magnesian silicates are well represented, and these rocks must have been in great part dolomitized prior to metamorphism.

Metamorphism of igneous rocks. Although the thermal metamorphism of plutonic rocks, lavas, volcanic ashes, *etc.*, has not yet received very much attention, it offers many points of interest and importance. Basic and sub-basic rocks are, as a rule, much more susceptible to this kind of transformation than acid ones. The most common case is that in which a volcanic series has been invaded and metamorphosed by subsequent plutonic intrusions.

Admirable illustrations are afforded by the Ordovician volcanic series of the Lake District in the neighbourhood of the granite masses of Shap and Eskdale and other intrusions[5]. The rhyolites near the Shap granite do not, as a rule, show any changes that can be clearly attributed to the effects of heat. Where, however, decomposition-products existed in the original rocks, they have given rise to metamorphic minerals. In particular, the green pinitoid substance is converted into a mixture of white and brown micas. The coarsely spheroidal ('nodular') rhyolites illustrate this point. The spheroids had, prior to metamorphism, been altered in the usual fashion into complex nodules having concentric shells of rhyolite substance and of weathering-products. In the metamorphosed nodules the shells of unweathered rhyolite remain unaltered, the flinty siliceous zones are converted into quartz-mosaic with a little mica, and the pinitoid substance is changed into biotite and muscovite. In the cracks which divided the shells there is sometimes a little blue tourmaline.

[1] Teall, *Mem. Geol. Sur., N.W. Highlands* (1907) 453–462.
[2] *Mem. Geol. Sur., Tert. Ign. Rocks Skye* (1904) 145–151.
[3] Clough and Pollard, *Q. J. G. S.* (1899) lv, 372–379.
[4] Coomaráswámey, *ibid.* (1903) lix, 91–103, pl. VI, VII.
[5] Harker and Marr, *ibid.* (1891) xlvii, 292–309, pl. X, figs. 4–6; and (1893) xlix, 360–365, pl. XVII, figs. 1–5; Walker, *ibid.* (1904) lx, 102–104.

The fragmental rocks associated with these rhyolites were of much less acid composition, and were probably more altered prior to the metamorphism. Hence they show more change, the production of biotite being often observed. As in argillaceous rocks, little spots relatively clear of mica are sometimes present: these show a crystalline reaction and may be andalusite. The spots disappear with more complete metamorphism, but crystals or grains of andalusite or cyanite are sparingly developed, and finally the rock is completely recrystallized into a finely granular mosaic with a certain amount of biotite, a little opaque iron-ore, *etc.* Relatively large crystals of felspar enclosed in the tuffs are replaced by a new felspar-mosaic, only the general outline of the original crystal being preserved.

The augite-andesites on the west side of the Shap granite afford fine examples of thermal metamorphism. They had undergone considerable change prior to the post-Silurian intrusion of the granite. Chloritic minerals, calcite, chalcedony, and quartz had been formed from the pyroxene and felspar, and were partly disseminated through the rock, but especially collected in little veins and in the vesicles. These alteration-products were the elements most readily affected by heat. The chloritic mineral has been converted into biotite, or, where it was associated with calcite, into green hornblende (notably in the vesicles): chalcedonic silica has been transformed into crystalline quartz. The rocks are more altered nearer the granite, and new minerals appear, such as a purplish-brown sphene, magnetite, and pyrites; the plagioclase phenocrysts are replaced by a mosaic of new felspar-substance; and finally the whole mass of the rock is found to be reconstituted, the ground becoming a fine-textured mosaic of clear granules. Mr Kynaston[1] has described similar effects in the Old Red Sandstone andesites bordering the Cheviot granite.

A more basic type of lava, on the north side of the Shap granite, shows phenomena on the whole very similar to the preceding; but, owing to the larger percentage of lime present, the minerals produced are in part different. Green hornblende predominates over biotite among the coloured constituents of

[1] *Tr. Edin. G. S.* (1901) viii, 18–26.

the metamorphosed rocks, and an augite, colourless in slices, is also formed, especially in veins and amygdales. Epidote is another characteristic mineral, and sphene, pyrites, and magnetite occur as before. Especially noteworthy is the formation of numerous lime-bearing silicates from the contents of the vesicles: grossularite occurs, as well as hornblende and actinolite, epidote, augite, and quartz. In the centre of the largest amygdales some residual calcite is found, recrystallized but not decomposed[1]. A basic hypersthene-bearing lava (the Eycott type) is metamorphosed by the Carrock Fell gabbro[2], the bastite pseudomorphs after hypersthene being converted into a pale hornblende. Here the transformation of the rocks is not always complete, the large labradorite phenocrysts being, as a rule, not recrystallized into a mosaic, but only cleared of their dusty inclusions (fig. 84). The metamorphosed Ordovician lavas near the Galloway granites[3] recall in many respects the Shap rocks. A lime-garnet is frequently met with, and new felspar occurs both in the body of the rock and in the amygdales.

The Tertiary basaltic lavas of Skye[4] are often considerably metamorphosed by the later intrusions of gabbro and granophyre. One interesting result is the formation of felspar in the amygdales. It is produced, together with epidote, zoisite, actinolite, *etc.*, mainly at the expense of soda-lime-zeolites. In the mass of the rock the chief change is usually the conversion of the augite to greenish fibrous hornblende. In the highest grade of metamorphism, however, hornblende is not produced, augite being found both in the body of the rock (recrystallized in common with the felspar) and in the amygdales (associated with new felspar which replaces zeolites).

The tuffs of basic and intermediate character near the Shap granite have much resemblance to the lavas as regards their metamorphism. Brown mica is the usual ferro-magnesian

[1] *Q. J. G. S.* (1893) xlix, 360–364, pl. XVII, figs. 1–4.

[2] *Ibid.* (1894) l, 332.

[3] Teall, *Ann. Rep. Geol. Sur.* for 1896, 47; *Mem. Geol. Sur., Silur. Rocks Scot.* (1899) 647–650.

[4] *Mem. Geol. Sur., Tert. Ign. Rocks Skye* (1904) 50–53, pl. XVII, figs. 4, 5; XVIII, fig. 1.

mineral formed, amphibole being less common. Magnetite is never abundant, and sphene is wanting. The most metamorphosed rocks are completely reconstituted into a very fine-textured aggregate of clear granules, in which lie flakes of biotite parallel to either original lamination or cleavage, producing a kind of mica-schist. Felspar crystals enclosed in the tuffs are either transformed into pseudomorphs of epidote or recrystallized into a mosaic.

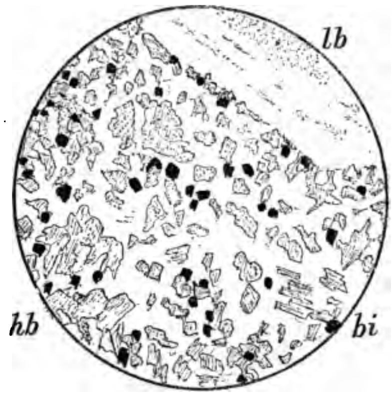

FIG. 84. METAMORPHOSED BASIC LAVA ENCLOSED IN THE GABBRO OF CARROCK FELL, CUMBERLAND; × 20.

The rock was originally a hypersthene-basalt belonging to the Eycott Hill group (see fig. 56). The porphyritic felspars have become clearer (*lb*), their large inclusions disappearing; the pyroxenes or their weathering-products have been converted chiefly into a pale hornblende (*hb*) or locally into biotite (*bi*); the magnetite has recrystallized in good octahedra; and the felspars of the ground-mass are now a clear aggregate, which appears almost homogeneous in natural light [1550].

Concerning the thermal metamorphism of abyssal and hypabyssal rocks the data are scanty, except as regards the commoner basic types. In granites and allied rocks the effects of metamorphism are first shown by such minerals as biotite and hornblende. Near Catacol, in the north of Arran[1], a dyke of vogesite is metamorphosed in contact with the Tertiary

[1] *Mem. Geol. Sur. Scot., Geol. N. Arran* (1903) 109.

granite. Each crystal of hornblende, about $\frac{1}{10}$ inch long, is replaced by an aggregate of biotite-flakes. A pale augite, which was also present in the original rock, shows a like transformation only in an incipient stage. The felspar seems to have undergone recrystallization.

Diorites are metamorphosed in the Malvern range, the results, however, being complicated by dynamic changes. As described by Dr Callaway[1], the chief effect clearly referable to heat is the replacement of hornblende by a deep brown biotite in the vicinity of an intruded granite. It appears that the hornblende had been, at least to some extent, previously converted into a chloritic mineral. The plagioclase is stated to give rise to white mica. The same author describes the metamorphism of diorite by a granitic intrusion in Galway Bay, where recrystallized plagioclase is observed, and the hornblende has given place to a chloritic mineral, epidote, and rarely biotite.

The Carrock Fell granophyre, in Cumberland, has produced metamorphism in a very basic type of gabbro. In some examples the apatite and iron-ores are unchanged, the turbid felspars become clear, and the augite is converted into green actinolitic hornblende or into biotite. The latter occurs chiefly near the grains of iron-ores, from which it has probably taken up some ferrous oxide and titanic acid[2]. In other specimens the gabbro shows more complex changes.

The metamorphism of dolerites by granitic intrusions has been noticed by Allport[3] in Cornwall, by Lossen in the Harz, *etc.* Specimens from these districts show in various stages the conversion of augite into hornblende and the recrystallization of the felspar. The hornblende produced is mostly green, but in the neighbourhood of the iron-ore (ilmenite) it is sometimes brown. Brown mica or scaly patches of chlorite may be found instead of hornblende, and these often give indications of being formed not directly from augite but from

[1] *Q. J. G. S.* (1889) xlv, 485, *etc.*

[2] *Ibid.* (1894) l, pl. XVII, fig. 4. See also Sollas on Carlingford district, *Trans. Roy. Ir. Acad.*, xxx, 493–496, pl. XXVI, fig. 8, XXVII, figs. 10–16.

[3] *Q. J. G. S.* (1876) xxxii, 407–427. For figures see Teall, pl. XVII, and XXI, fig. 2.

its decomposition-products. In the Isle of Skye[1] similar effects are to be observed in dolerite dykes cut off and metamorphosed by the granite of Beinn an Dubhaich (fig. 85).

FIG. 85. METAMORPHOSED DOLERITE DYKE, CLOSE TO GRANITE, KILCHRIST, SKYE ; × 20.

The augite is totally transformed to a pale, rather fibrous hornblende, except round the granules and skeletons of iron-ore, where its place is taken by biotite. The felspar crystals have become quite clear, but narrow chloritic veins traversing them have been converted to hornblende [3207].

Metamorphism in crystalline schists, etc. On this subject there is not a large amount of information, and it appears that crystalline schists of various kinds are, as a whole, less susceptible to thermal changes than sedimentary rocks. The metamorphism of phyllites and mica-schists has been studied in the Adamello range, in the Riesengebirge, in New Hampshire[2], on the Hudson River[3], *etc.* In some respects the phenomena resemble those seen in argillaceous strata, the production of biotite, andalusite, *etc.*, being characteristic; but there are sometimes quite special peculiarities, in particular

[1] *Mem. Geol. Sur., Tert. Ign. Rocks Skye* (1904) 319.
[2] Hawes, *A. J. S.* (1881) xxi, 21–32.
[3] G. H. Williams, *ibid.* (1888) xxxvi, 254–266.

the formation of minerals very rich in alumina. Cordierite is sometimes extremely abundant, while pleonaste and other spinels and pure corundum are noted in several localities.

In the southern Highlands of Scotland Mr Clough[1] has observed the crystalline schists to be metamorphosed by the granitic intrusions near Loch Lomond. Within a mile of the junction the albite-schists begin to develop small prisms of andalusite, which increase in size and abundance, and at the same time nests of dark mica become plentiful.

[1] *Mem. Geol. Sur. Scot.*, *Geology of Cowal* (1897) 98: see also Cunningham-Craig, *Q. J. G. S.* (1904) lx, 25, 26, pl. v.

CHAPTER XXI.

DYNAMIC METAMORPHISM.

In this chapter will be noticed some of the effects, mineralogical and structural, produced in rock-masses by the operation of great mechanical forces. Among the mineralogical changes we ought logically to separate those due to pressure from those due to mechanically generated heat, the latter belonging rather to the preceding chapter. This distinction we shall make, so far as our actual knowledge goes.

The consideration of dynamic metamorphism in comparatively yielding rock-masses has already been partly anticipated in the chapter devoted to argillaceous sediments: phenomena more striking, or at least more easily investigated, are now to be noticed in crystalline and other rocks of more stubborn consistency.

Strain-phenomena in crystalline rocks. A frequent effect of strain in the component crystals of a stubborn rock-mass is a modification of the optical properties, which at once becomes apparent between crossed nicols. Instead of being dark throughout for certain definite positions, a crystal shows dark shadows which move across it as the stage is rotated, owing to the directions of extinction varying from point to point. These *strain-shadows*[1] are best seen in quartz, and are very common in the granitic and gneissic rocks, quartzites, *etc.*, of countries like the Scottish Highlands.

[1] Mr Blake styled this appearance 'spectral polarization.' It is spoken of by some foreign writers as 'undulose extinction.'

Flexible minerals, such as micas, often show *bending* of their crystals, or, again, have yielded by a shearing movement, analogous to lamellar twinning, parallel to definite directions known as *gliding-planes* (fig. 86, *A*). In some minerals, such as the plagioclase felspars, the gliding-planes coincide with natural twin-planes[1], and the *secondary twinning* can be distinguished from original lamellation only by its inconstant character and its relation to bending or other strain-phenomena

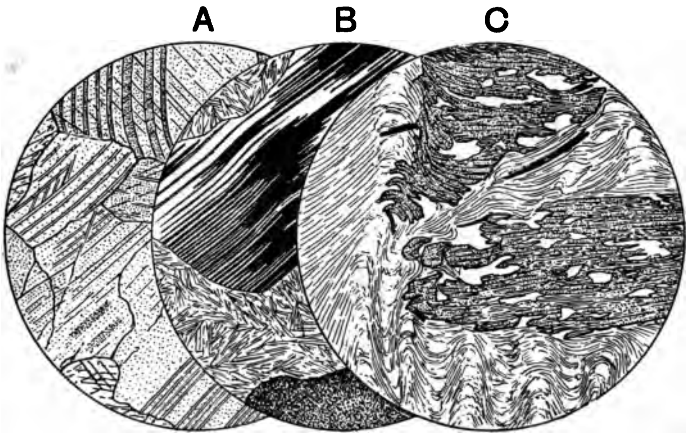

FIG. 86. STRAIN- AND CATACLASTIC EFFECTS.

A. Secondary twin-lamellation in calcite; × 20; in crystalline limestone, Mt Gendres, Pyrenees [5245].

B. Secondary twin-lamellation in plagioclase felspar; × 20, *crossed nicols*: in gabbro, Pen Voose, Lizard, Cornwall. The matted fibrous aggregate is actinolite, replacing diallage [2475].

C. Crushed Staurolite-Mica-schist, Lukmanier Pass, Lepontine Alps; × 13. Here dynamic has followed upon thermal metamorphism. The staurolite crystals have been shattered, and the foliation-surfaces, marked by the arrangement of the mica-flakes, have been thrown into minute folds. Clear quartz occupies the loops of the folds, as well as the crevices made by the fracture of the staurolite crystals [2394].

[1] Judd, *Q. J. G. S.* (1885) xli, 363–366, pl. x, fig. 1.

(fig. 86, *B*)[1]. Sometimes in one crystal, the closeness of the secondary lamellæ is seen to increase, with the strain, until the crystal has yielded along a crack or a granulated vein. In some rocks there seems to be evidence of the microcline-structure being set up in orthoclase as a result of strain.

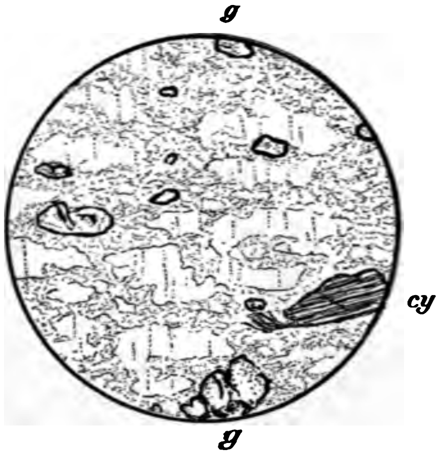

Fig. 87. GARNET-GRANULITE, RÖHRSDORF, NEAR CHEMNITZ, SAXONY; × 20.

Showing grains of garnet (*g*) and imperfect prisms of cyanite (*cy*) set in a granular aggregate of felspar and quartz. The latter shows a parallel arrangement of its larger elements, and there are rows of fluid-pores traversing the rock at right angles to the parallel-structure [835].

Quartz sometimes shows *rows of fluid-pores* marking directions of shearing-strain (fig. 87), and perhaps parallel to actual planes of faulting if the crystal has yielded[2]. The lines of pores may be traceable through contiguous crystal-grains; or entering another mineral, such as felspar, they may become actual planes of discontinuity.

It appears that the *schiller-structures*[3], so characteristic of certain minerals in deep-seated rocks, may also be produced

[1] *Cf.* Cohen (3), pl. LXXIX.
[2] Judd, *M. M.* (1886) vii, 82, pl. III, fig. 1.
[3] Judd, *Q. J. G. S.* (1885) xli, 374–389, pl. X–XII; *M. M.* (1886) vii, 81–92, pl. III.

as secondary phenomena by pressure. A typical structure is that in which cavities of definite form and orientation ('negative crystals') are developed along certain planes, and filled, or partially filled, by material dissolved out from the enclosing crystal. Hypersthene affords a good example. The 'solution-planes' (Ger. Lösungsflächen) proper to a mineral are parallel to one or more crystallographic planes; but after a secondary lamellar twinning has been set up in a crystal, the gliding-planes become the easiest solution-planes. Pyroxenes, felspars, and olivine are minerals often affected by schiller-structures.

Crystals of brittle minerals subjected to stress have often yielded by actual *cracks*, which may have a definite direction

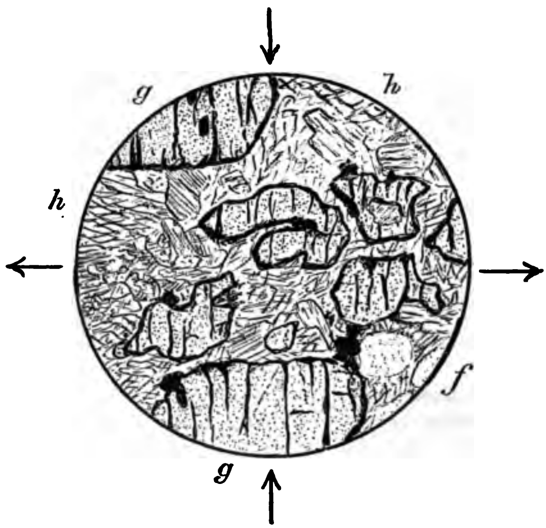

FIG. 88. HORNBLENDE-ECLOGITE (GARNET-AMPHIBOLITE), LOCH LAXFORD, SUTHERLAND; × 15.

Consisting of red garnet (*g*) and green hornblende (*h*), with only a little clear quartz, turbid felspar (*f*), and opaque iron-ore. The arrows show the direction of the stresses that have operated in the rock, and the brittle garnets are traversed by a strongly marked system of cracks perpendicular to the direction of tension [1254].

throughout the rock, being perpendicular to the maximum tension, and so parallel to the maximum pressure. This is sometimes seen in quartz and felspars, but most commonly in garnet (fig. 88). As a further stage, the portions of a fractured crystal may be separated and rolled over, or drawn out in the direction of stretching or flowing movement in the solid rock (compare staurolite in fig. 86, *C*). It is noticeable that quartz shows these phenomena much oftener than felspar: the former mineral, though harder than the latter, is more brittle.

Cataclastic structures. The phenomena of internal fracture and crushing of hard rocks ('cataclastic' structures of Kjerulf) are to be seen in endless variety in some regions of great mechanical disturbance. They may be developed in less or greater degree; they may affect some or all of the mineral constituents of a composite rock; they may or may not tend to a parallel arrangement of the elements. In one type the rock-mass breaks up along definite surfaces of sliding, the material bordering the cracks being often ground down by friction: this is *brecciation in situ.* The irregularly intersecting surfaces divide the rock into angular fragments; but these may be rolled over and their angles rubbed off, so that a 'friction-conglomerate' as well as a 'friction-breccia' may arise, especially along faults and thrust-faults (*e.g.*, Lake District). According as the new structure is on a large or a small scale, the fragments may be recognizable pieces of rocks or portions of constituent crystals of an originally crystalline rock.

Again, we sometimes find the larger elements of a rock—grains of quartz, crystals of felspar, *etc.*—surrounded by a border of finely granular material furnished by the grinding down of the crystal itself and adjacent ones. This is the *morter-structure* (Ger. Mörtelstructur) of Törnebohm. As a further stage, the finely granular portion of the rock may make up the chief part of its bulk, forming a matrix which encloses portions of crystals not destroyed but indicating by irregular polarization their strained condition (figs. 89, *C* and 90).

In many cases mechanical forces having a definite direction have caused uncrushed fragments to assume an eye-shaped or

lenticular form (Ger. Augenstructur) with their long axes perpendicular to the maximum pressure, and so parallel to one another and to any schistose structure in the matrix (figs. 89, *A* and 90). In such cases the crushed matrix usually has a

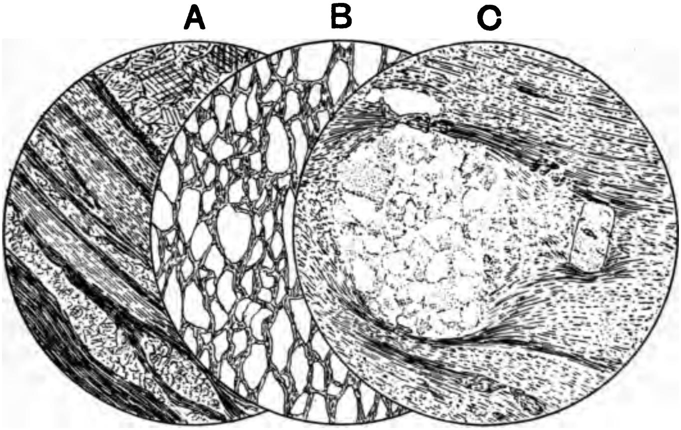

FIG. 89. CATACLASTIC EFFECTS.

A. Crushed Limestone, Devonian, Ilfracombe; × 20. With unbroken 'eyes': part of one is shown in the upper part of the field, and smaller ones in the lower part [783].

B. Schistose Grit, North Glen Sannox, Arran; × 13. Showing parallel orientation of quartz-grains [5034].

C. Crushed Quartz-porphyry dyke, Dhoon, Isle of Man; × 13. With an 'eye' of rock which has escaped crushing [2254].

more or less well-marked parallel structure or *schistosity*, in part analogous to slaty cleavage. The final result of the grinding down and rolling out processes is the type of rock named *mylonite* by Professor Lapworth[1], in which, except perhaps for occasional uncrushed 'eyes,' all original structures are lost. In these much-crushed rocks the 'eyes' no doubt represent in many cases porphyritic crystals, usually of felspar, in what was once an ordinary igneous rock. It is evident, however, that,

[1] See Page (Lapworth), *Introd. Text-book Geol.* 12th ed., figs. on p. 107.

in the absence of such indications, it must often be impossible to determine by microscopical study alone the nature of a rock whose original structures have been totally obliterated.

Mineralogical transformations. In extreme stages of crushing of crystalline rocks, the changes produced are by no means purely mechanical. In consequence of the stress and subsequent relief a *recrystallization* of minerals may be effected, resulting in the clear, finely granular aggregate which forms a large part of some dynamo-metamorphic rocks[1]. It must be remembered, however, that thermal metamorphism due to mechanically generated heat may complicate the strictly dynamic changes.

Further, atomic as well as molecular rearrangement has operated in greater or less degree in any dynamo-metamorphic rock not of the simplest constitution. Certain *mineralogical transformations* seem to be characteristic of dynamical metamorphism, being either developed by the action of great pressure or at least facilitated by pressure even when they can also take place without that condition[2]. It should be noticed that in crystalline, and generally in hard, rocks, these mineralogical changes begin before any important structural modifications are produced.

One characteristic change is the production of colourless mica at the expense of alkali-felspars. The mineral may be formed at the margin of a crystal squeezed against its neighbours or on surfaces of lamination or of movement in a felspathic rock: in such cases it takes the filmy form known as sericite (fig. 89, *C*). Potash-felspar gives rise to muscovite, soda-felspar to paragonite.

A characteristic alteration in the soda-lime-felspars results in the minutely granular aggregate which has been called 'saussurite,' and is not always of precisely the same nature[3]. The soda-bearing silicate of the felspar separates out as very minute clear crystals of albite, while the lime-bearing silicate,

[1] *Cf.* Teall, p. 175, figures.

[2] See G. H. Williams, *Bull.* 62 *U. S. Geol. Sur.* (1890) Ch. I.

[3] Teall, 149–152. For a somewhat similar process of 'granulation' of plagioclase resulting in a fine mosaic of albite, *etc.*, see Hyland, *G. M.*, 1890, 205–208. *Cf.* Williams, *l.c.*, 58–60, 68, 69, figures.

in conjunction with other constituents of the rock, goes to form minerals rich in lime. Zoisite is a characteristic mineral, or its place may be taken by yellow or colourless epidote; and needles of actinolite may also occur. (See p. 83.)

The conversion of plagioclase into scapolite under dynamic action is a more complex process, involving the accession of sodium chloride in solution[1].

Other changes common in dynamic metamorphism are the conversion of olivine into tremolite or anthophyllite and talc, and the production of granular sphene at the expense of ilmenite or other titaniferous minerals. Augite gives rise when crushed to chlorite. The conversion of augite or other pyroxenes into green hornblende is also a common feature in regions of dynamic metamorphism: perhaps this is one of the transformations that should be ascribed to the heat generated in the crushing. It is a very wide-spread phenomenon[2].

The borders ('reaction-rims') sometimes noticed at the junction of two different minerals in a crystalline rock have in many cases been attributed to dynamic metamorphism. (See above p. 82.)

Illustrative examples. In many parts of the Scottish Highlands, the phenomena of dynamic metamorphism are exhibited on an extensive scale[3]. In those parts of western Sutherland where the cataclastic effects attendant on the great Mid-Palæozoic crust-movements have been specially developed, it is possible to trace the successive stages in the crushing down of the Lewisian gneiss, the Torridonian sandstones, and the Cambrian quartzites. Mere strain-effects and incipient fracture of crystals give place to more or less complete crushing, with 'morter' and 'eyed' structures (fig. 90), and in places a strong schistosity of the 'mylonite' type.

Some of the observed changes are perhaps to be ascribed rather to the effects of mechanically generated heat than to

[1] Judd, *M. M.* (1889) viii, 186–198, pl. IX.
[2] See, *e.g.* R. D. Irving, *A. J. S.* (1883) xxvi, 27–32; G. H. Williams, *ibid.* (1884) xxviii, 259–268; Teall, *Q. J. G. S.* (1885) xli, 133–144.
[3] *Geol. Struct. N.W. Highlands, Mem. Geol. Sur.* (1907).

pure dynamic metamorphism. Thus, near Loch Assynt and in other places, the Lewisian gneiss is traversed by zones of crushing, within which the rock is completely reconstituted, and from the granitoid assumes the 'granulitic' structure.

FIG. 90. ADVANCED CATACLASTIC STRUCTURE IN GNEISS, SOUTH SLOPE OF BEINN MÒR OF ASSYNT, SUTHERLAND; × 20.

The greater part of the rock is completely broken down, and has partly taken on the parallel structure of a mylonite. A large grain of quartz is only partly crushed, and this between crossed nicols shows strain-shadows [1641].

The rock so metamorphosed shows a rather fine-textured mosaic of clear quartz and felspar, enclosing imperfect crystals of green hornblende and ragged flakes of brown mica instead of the original pyroxene. There is a marked parallel structure and some tendency in the several minerals to collect into little lenticular aggregates. Again, some dykes show very clearly the conversion of dolerite into hornblende-schist, and an instance of this has been described in detail by Dr Teall[1]. The augite is transformed into green hornblende, and the felspar has recrystallized in water-clear grains, while the titaniferous iron-ore has also been altered, giving rise frequently to granular sphene. These mineralogical changes may be

[1] *Q. J. G. S.* (1885) xli, 133–144, pl. II; *Brit. Petr.*, pl. XIX, XX, pp. 197–200.

produced without any schistose structure, but the massive hornblendic rock further becomes in places a typical hornblende-schist. This is at Scourie: other examples are seen near Unapool, on Loch Glencoul, and near Loch Assynt (fig. 91). Near Lochinver dykes of enstatite-peridotite pass into an anthophyllite-schist, consisting of matted aggregates of anthophyllite prisms or needles with little patches of brilliantly polarizing talc and large rhombs of carbonates[1].

FIG. 91. AMPHIBOLITE OR HORNBLENDE-SCHIST, FROM THE METAMORPHISM OF A DOLERITE DYKE, LOCH ASSYNT, SUTHERLAND; × 20.

The rock now consists essentially of idiomorphic hornblende and clear secondary felspar, with some magnetite. The slice is cut parallel to the schistosity, which therefore is not apparent in the figure [1664].

In the district farther east there are some phenomena which seem to point to thermal effects, *e.g.* the production of brown mica in the Torridon Sandstone near the 'Beinn Mòr thrust-plane.' But, in proportion as the rocks affected give evidence by increasing schistosity of thorough mechanical degradation and sliding movement, those mineralogical transformations which seem to belong to pure dynamic metamorphism become

[1] Dr Teall speaks of one of these rocks as a talc-gedrite-siderite-schist. In other examples the amphibole mineral is a monoclinic one (tremolite).

more general. Near the great 'Moine thrust-plane' the sericitization of the acid rocks and the chloritization of the basic ones reach their fullest development in connection with the maximum display of mechanical deformation. Detailed petrographical observations on this interesting district have only recently been published.

Illustrations of dynamic metamorphism are furnished in the Central Highlands and in Ireland by various members of the 'Dalradian' series of Sir A. Geikie. The so-called 'green schists' are ascribed by that geologist partly to the crushing of basic lavas and tuffs. Some of these rocks again have the appearance of intrusive dolerites, in which every stage of crushing into chloritic schists, *etc.*, can be traced (North Esk, Kincardineshire).

The name 'amphibolite' has often been applied to rocks, usually more or less markedly schistose, in which hornblende is the dominant mineral. Many of them are doubtless the results of dynamic action on diorites and sometimes on dolerites and gabbros. Two or three types from the Scottish Highlands have been figured by Dr Teall, including an epidote-amphibolite from Glen Lyon, Perthshire[1], and a zoisite-amphibolite from near Beinn Hutig, in Sutherland[2].

Gradual transitions from massive diorite to hornblende-schists may be studied in Anglesey, especially between Holland Arms or Gaerwen and Menai Bridge[3]. In the processes by which these schistose rocks have been produced the felspar has often been destroyed, and is represented in great part by epidote, which is often abundant. The granular sphene, which is often seen, is probably derived in part from ilmenite, as well as from the original sphene of the diorite. The hornblende has recrystallized in imperfect elongated crystals of green colour with marked parallel orientation. Locally the place of this mineral is taken by a beautiful pleochroic glaucophane, and a rock near the Anglesey Monument[4] is a glaucophane-

[1] Teall, pl. XXVIII, fig. 2.

[2] *Ibid.*, pl. XL, fig. 2. *Cf.* actinolite-schist with zoisite, pl. XXVIII, fig. 1.

[3] Blake, *Rep. Brit. Ass. for* 1888, 406.

[4] Blake, *G. M.*, 1888, 125–127; Teall, pl. XLVII, figs. 1, 2; *20th Cent. Atlas*, 39, with plate.

epidote-schist, with little trace of any other mineral, except veinlets of clear secondary felspar. The pleochroism of the glaucophane (bright blue to pale lilac) and the epidote (yellowish green to pale yellow) makes a slice of this rock a very striking object.

The 'porphyroids' of some authors are, for the most part, quartz-porphyries more or less modified by dynamic metamorphism. They have received a rough schistosity, which is accentuated by films of 'sericitic' mica, formed at the expense of the felspar. The rock of Sharpley Tor in Charnwood Forest is a good example. Similar features are shown by the Llanberis mass of quartz-porphyry at numerous points on its south-eastern edge, especially near Llanllyfni.

The phenomena of dynamic metamorphism in argillaceous sediments (phyllites, *etc.*) have received some notice in a former chapter. The other groups of sedimentary rocks have been less studied from this point of view. To some of the phenomena observable in the arenaceous rocks and quartzites of Sutherland[1], culminating in complete mylonitization, we have already alluded. Interesting mechanical effects are produced where alternating gritty and slaty beds have been subjected to crushing. Some remarkable cases have been described by Mr Lamplugh in the Skiddaw Slates of the Isle of Man; and Prof. Watts has shown how the structures seen in the field are repeated on a small scale in slices of the rocks[2].

Calcareous rocks again are susceptible of considerable transformations, chiefly of the nature of structural rearrangement, when subjected to intense mechanical forces. Excellent examples are afforded by the Ilfracombe and other Devonian limestones, to which Dr Sorby[3] drew attention many years ago. These often show, not only a highly developed slaty cleavage, but also a deformation of the individual fragments (such as crinoidal remains, *etc.*) of which they are largely composed, besides curious phenomena resulting from solution having

[1] Teall, pl. XLVI, fig. 2.

[2] *Q. J. G. S.* (1895) li, 563–597, pl. XX, XXI; *Mem. Geol. Sur., Geol. I. Man* (1903) 100–104.

[3] *Phil. Mag.* (1856) xi, 26–34; *Pres. Addr.* 1879, *Q. J. G. S.*, XXXV *Proc.*) 57–59. See also Marr, *G. M.*, 1888, 218–221.

proceeded at the places of greatest pressure with simultaneous crystallization at the places of greatest relief. The cleaved limestones near Ilfracombe have a microscopic 'eyed' structure, owing to the preservation of uncrushed lenticles of the original rock (fig. 89, *A*). The salite-bearing limestone of Tiree[1] in the Hebrides also illustrates well the crushing of a crystalline calcareous rock and the production of a fluxional schistose structure of varying perfection. This structure winds past the more resisting grains of salite, felspar, *etc.*, and in the corners of the 'eyes' so left are uncrushed relics of the original calcite-mosaic.

In America one of the most comprehensive studies of a region of dynamic metamorphism is perhaps that by G. H. Williams of the 'greenstone-schists,' *etc.*, of the Lake Superior region, which further contains a general summary of knowledge on the subject[2]. The dominant types of rocks in the areas there studied have been basic eruptives, probably true lavas in great part, and these are now represented by chlorite- and hornblende-schists. Gabbros, diorites, granites, and quartz-porphyries have also been included, and show their appropriate types of alteration. The author traces in detail the processes of uralitization, chloritization, epidotization, saussuritization, sericitization, *etc.*, as well as the structural changes undergone by the rocks.

Interesting phenomena of dynamic metamorphism have been described by Smyth in the gabbros of the Adirondacks at Russell, St Lawrence County, N.Y.[3] The original rocks consisted essentially of labradorite and augite. From the former mineral has arisen scapolite and sometimes a saussurite-like aggregate; from the latter a scaly green hornblende. In a further stage of alteration cataclastic effects become marked, all the constituents becoming granulated, while the hornblende increases in amount. In the final stage the rock has taken on a gneissic structure, the cataclastic features are lost in total

[1] Bonney, *G. M.*, 1889, 485; Coomáraswámey, *Q. J. G. S.* (1903) lix, pl. VI.

[2] *The Greenstone Schist Areas of the Menominee and Marquette Regions of Michigan*, *Bull.* 62 *U. S. Geol. Surv.* (1890) Ch. I, VI, figures and plates.

[3] *A. J. S.* (1896) i, 273–281.

recrystallization, the scapolite has been reconverted to felspar, but of a more acid variety than the original labradorite, and part of the hornblende seems to have passed again into augite.

Among other examples which might be selected, an interesting one is that of the rhyolite-gneiss of Berlin in Wisconsin[1]. Here the chief transformations to be noted are the setting up of a microperthitic structure in the plagioclase phenocrysts and the recrystallization and orientation of the ground-mass.

[1] Weidman, *Bull. Geol. and Nat. Hist. Sur. Wis.* No. III (1898).

INDEX.

[*Some rock-names are given here which are not admitted into the text. The list will thus serve to some extent as a glossary.*]

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